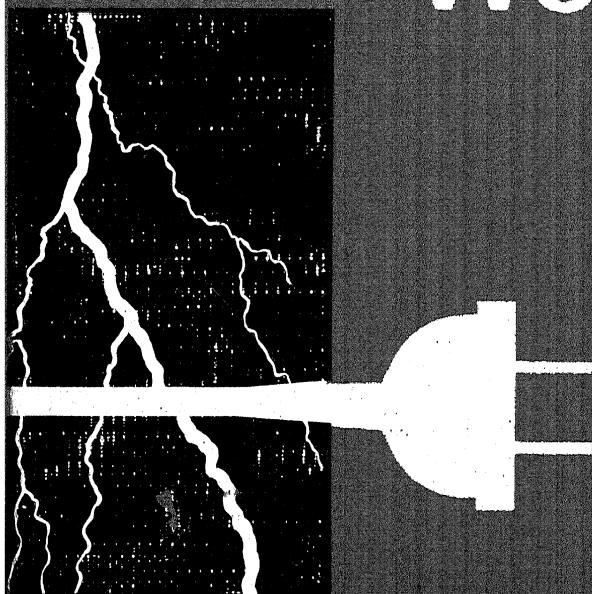


Making Electricity Work



by John M. Kennedy

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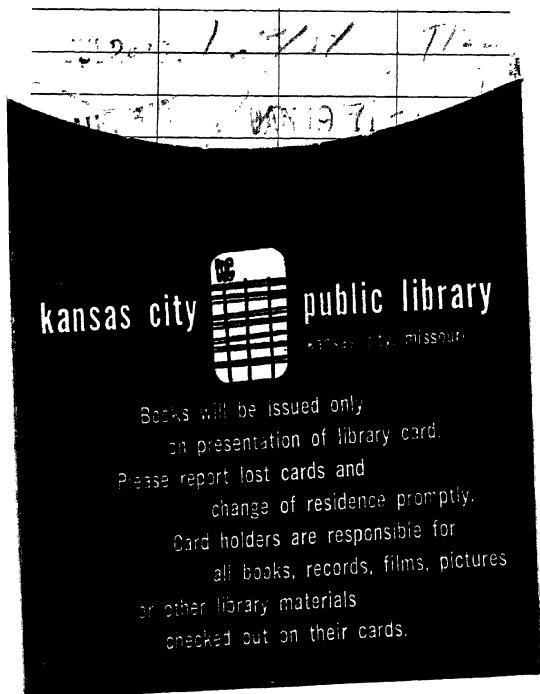
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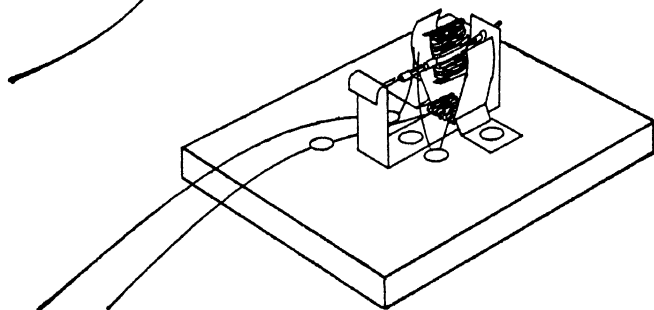
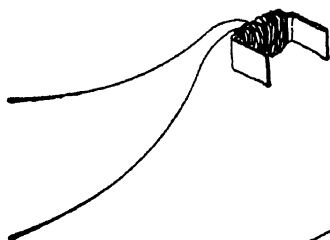
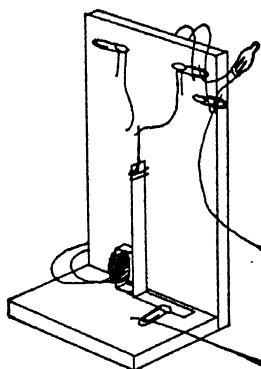
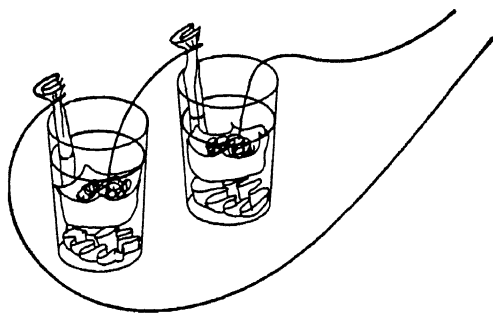
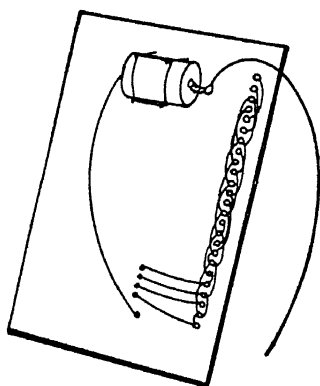
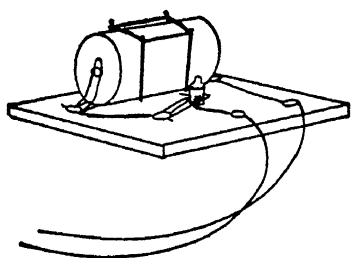
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~~~~~ MAKING ELECTRICITY WORK



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~~~~~ ELECTRICITY WORK

BY JOHN M. KENNEDY ~~~~~

~~~~~ ILLUSTRATED BY THE AUTHOR

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TO THE READER ~~~~~

This is a book about electricity and its first cousin, magnetism. As you read the book and learn how electricity and magnetism work, you will probably want to make many of the games and devices described in the book, and as you make these you will find yourself learning more and more about basic electricity. Since understanding the principles is more important than merely building the devices, the plans have been carefully worked out to make the construction simple and to use easily obtainable materials wherever possible.

Very few tools are required. You probably have a hammer, pliers, a ruler, scissors, and a paring knife. You will need a small pair of tin snips. The pieces of wood for the projects can be of almost any size. But if you can't find suitable pieces or get them cut, you will also need a saw.

You will find most of the necessary materials around the house—aluminum foil, household bleach, Scotch Tape, needles, drinking glasses, coffee cans, and the like. Except for two special items, all the rest of the materials can be obtained in neighborhood stores. Here is what you will need:

Some common paper clips about $1\frac{1}{4}$ inches long, like the ones in Fig. 1-4. You will need more than 100 for all the projects, so start with a box of 100.

A handful of wire-finishing nails of the size called four-penny. Finishing nails are the kind with almost no head, like the ones in Fig. 1-7.

Some upholsterer's nails. These are nails with thin shafts $\frac{1}{2}$ to $\frac{3}{4}$ inches long and with rounded heads $\frac{1}{4}$ to $\frac{1}{2}$ inches in diameter, like the ones in Fig. 1-4. The heads can be smooth or dented, but they must have an unpainted metal finish such as chromium or copper which will carry electricity. You will see how this works in Chapter 1. You will need about 130 for all the projects, but start with a card of 25 or so.

About 50 flat washers like the ones in Fig. 2-1. They should be about $\frac{1}{2}$ inch in diameter with the small hole in the center not much more than $\frac{1}{8}$ inch in diameter. They should be thick enough so that you can't bend them with your fingers. Get them at your neighborhood hardware store.

Flashlight batteries of the size called D. These have almost the same diameter as a fifty-cent piece. Start with one or two.

Flashlight bulbs. There are many kinds. You will need "pen-light" bulbs, which have an odd shape (see Fig. 1-7) because the glass tip is formed to act as a lens. They have a threaded base. The box or the bulb should be marked "1.2 V" (volts) and ".22 A" (amperes). If these markings are on the box and not on the bulb, then the box *and* the bulb should be marked with the same number—which is 112 if the bulbs are made by General Electric or Westinghouse. You will need eight for all the projects, and occasionally one will burn out. Start with one or two.

A small piece of sandpaper.

A coil of bell wire or hookup wire. The best kind has a plastic insulation or outside covering which is easy to remove when you make connections. The wire inside should be one solid piece of size 20 or 22. (These numbers are American Wire Gauge or Brown and Sharpe.) The coils in the five-and-ten or the housewares store probably won't be marked with the size. Select a size which you can bend easily with your fingers.

Some two-wire plastic-coated lamp cord. Since you will use it to connect mostly between parts of a project which are in

TO THE READER

separate rooms, you will have to decide how much you need when you get to the projects. You will need two feet of it to make an electric battery. It costs about five cents a foot.

A small alnico magnet about $\frac{1}{8}$ inch square and 1 inch long. Get the straight-bar type and not the kind in the shape of a U. These magnets are often used in magnetic novelties, such as the magnetic pot holders which stick to the side of a stove. "Gift" mail-order houses usually sell alnico magnets ten for a dollar.

The two special items can be obtained at radio-part stores or mail-order radio-supply houses. You will need a *neon glow bulb* with wire leads; order General Electric's type NE-2 or the equivalent bulb made by another manufacturer. You will also need 250 feet or more of No. 30 American Wire Gauge *plain enamel magnet wire*. Probably the smallest spool you can buy will be $\frac{1}{4}$ pound (about 800 feet) but even that much will cost under a dollar.

If you are careful about asking for the right materials, you should have little difficulty or expense in getting them, and you will be able to concentrate on the constructions and their underlying principles.

A number of persons helped and encouraged me in the preparation of this book. Mr. D. B. Cameron, of the National Carbon Company, and Mr. J. J. Coleman and Mr. P. E. Krouse, of the Burgess Battery Company, made helpful suggestions for the battery chapter. Particular thanks are due to Mr. Arthur J. Cipriani and his associates at the Ray-O-Vac Company for their contributions to that chapter.

David Klein helped in important ways to make the book take form. Mrs. Manoel F. Behar did yeoman service at the typewriter. It is not possible to thank either of these two enough.

New York, New York
June 1959

J. M. K.

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CHAPTER I

WHAT IS ELECTRICITY?

The brilliant and powerful bolt of lightning, the toaster and the washing machine, the neon sign and the television set, all depend for their action upon a tiny particle of matter called the *electron*. Since all the useful and enjoyable results of electricity—and all the things that we shall deal with in this book—depend upon a stream of many millions of these electrons, it's a good idea to get acquainted with the electron right at the start.

WHAT IS AN ELECTRON?

All matter, all material substances, are built up out of atoms, which are the basic building blocks of everything in the world—coal and steel and rocks, and even people, for that matter.

The atom consists of a center, or nucleus, and around the nucleus one or more electrons travel in orbits, or paths, like tiny planets around a sun. The nucleus holds the or-

MAKING ELECTRICITY WORK

biting electrons by a force of attraction called a *positive charge*, and the nucleus of each basic substance, or element, attracts a different number of electrons. Electrons are *negatively charged*, and in addition to being attracted to the nucleus they repel each other.

It is this charged state of the nucleus and electrons that interests us in our study of electricity. Normally, enough electrons orbit around the nucleus to balance its positive charge with their negative charges so that the atom is neutral even though the positive and negative charges are still there. But it is possible to strip one or more of the orbiting electrons off an atom. Then the atom is left positively charged and the place to which the electrons are moved becomes negatively charged.

The electrons move more readily than the nucleus, partly because the nucleus is very heavy compared to the electrons. Each nucleus is 2000 to 400,000 times as heavy as an electron. Not that any of them weighs very much. It would take about 500,000,000,000,000,000,000,000,000 electrons to weigh a pound.

ELECTRONS IN MOTION 9

Electricity is, as we have said, electrons in motion in a stream, or current. Great masses of electrons, stripped off atoms and flowing through carefully arranged channels, produce electricity's useful work. In some arrangements of channels, the flow of electrons produces heat to cook food, melt steel, or warm a bed. In other arrangements, the flow can drive a train, lift an elevator, or turn a fan. In still others, it can plate metals or manufacture chemicals.

Always, though, it is the movement that produces the desired results.

Conductivity and Conductors

But electrons will not move with equal ease through all substances. They will move easily through some substances, less easily through others, and through still others only with great difficulty. What determines this *conductivity*, or ability of a substance to pass electrons, is the ease with which electrons can be stripped off the atoms of which the substance is composed. If electrons are removed easily, electricity will flow freely.

The reason for this is that electrons do not flow through a substance as water flows through a porous sponge. As electrons are pushed into one end of a piece of a substance—a length of copper wire, for example—by a battery or other source, they are repelled by the electrons orbiting about the atoms of the copper. The first electrons to enter the wire have to be pushed hard enough by the repulsion of the electrons coming behind them to overcome a solid wall of repulsion presented by the electrons of the copper in front of them. As the newly arrived electrons come closer and closer to the electrons of the copper, the force of repulsion between them becomes greater and greater, just as a spring resists more and more as it is compressed. Finally, some of the newly arrived electrons push past the orbiting electrons of the nearest atoms of the copper and are repelled by the electrons of the next atoms. Other electrons push orbiting electrons off atoms and take their places. The harder it is to strip an electron off an atom,

the harder it will push back against an oncoming electron, even if the electron pushes by and doesn't strip it off. The electrons are forced ahead by the repulsion of the oncoming electrons behind them and work their way down the wire against the repulsion ahead of them, either passing by atoms of the copper or replacing electrons, like ball players when the bases are loaded.

This force of repulsion surges through the conductor at the speed of light, about 186,000 miles a second. Thus, when an electric current enters a conductor, its force is felt at the other end almost instantly. However, the electrons that form the current move much more slowly. This is the same as the way the force of water in a dam or water tower pushes other water out of your faucet the moment you open it, but yet you would have to leave the faucet open for hours or days before water from the dam or water tower made its way to your faucet.

If the substance is such that electrons can be easily stripped off its atoms, then the flow of electrons through it will be rapid. If electrons can be stripped only with difficulty, the flow will be slower, or a greater driving force or voltage will be required from the source to obtain the same flow. In some substances—insulators—almost no electrons flow at all unless the driving force is very great. Yet in all three cases the *force* of the electric current is felt at the other end of the substance at the speed of light. In insulators, very sensitive instruments would be needed to detect it, but it is there.

The substances from whose atoms electrons are most easily stripped (and which can therefore carry or conduct

electric current most easily) are the metals. In general the nonmetals are poor conductors because their electrons are removed with difficulty. Copper, silver, and gold are about the most efficient conductors of electron flow. Where the most efficient conduction is needed—for example, in bringing electrons to a motor—copper is usually used. It is much cheaper than gold or silver, and it is such a good conductor that very little heat is generated and lost before the current gets to the motor. Aluminum is not quite so good a conductor as copper, but it weighs less. It can be made into wires with a steel center to make it as strong as copper. Such a wire is lighter and cheaper than a copper wire which will carry the same current. Being lighter, it requires fewer supporting towers, and these can be placed farther apart.

Many substances are only fair conductors; that is, they generate considerable heat as a current passes through them. Hence they are used where it is desired to generate heat. A certain alloy of nickel, chromium, and iron, called *nichrome*, is a fair conductor, or what is called a good resistance material. Because it can reach a high temperature without burning up, it finds use in toasters and grills and similar heating devices.

Glass, cloth, and certain plastics are poor conductors. Where poor conduction is needed—for example, to keep electrons from short-circuiting, or flowing where they are not wanted—these kinds of substances are used. It is the poor conductors that are called *insulators*. We are lucky that air is a good insulator. If it weren't, it would short-circuit all electrical equipment. Batteries would run down

MAKING ELECTRICITY WORK

in minutes, and current would run out of one slot in the wall plug and into the other while the electric meter spun. A minute amount of current does flow through the air and all other insulators, however. When the voltage, or push behind the current, is increased, the flow through such insulators increases. In the case of lightning, the voltage rises so high that the air loses its insulating properties and massive currents flow through it. With the device you will build first (see p. 9), you will be able to test many substances to see whether they are good conductors, fair conductors, or insulators.

HEAT AND ELECTRICITY

While an electron is pushing against the repulsion of the electrons of an atom, the whole atom is slightly displaced from its position within the solid structure of the substance. Then, as the moving electron passes by the atom or replaces an electron in it, the atom springs back into place. So, as a current of electricity flows through a substance, there is a continuous agitation of the atoms within the substance. The greater the resistance of a substance—that is, the harder it is to strip electrons from its atoms—the greater the agitation of the atoms as a current flows. Because agitation of its atoms makes a substance hot, many practical uses can be made of this property of a current of electrons. A little later in this chapter you will be working with a flashlight bulb, a device in which a substance (the metal filament) gets so hot that it gives off light.

To illustrate for yourself the heating effect of an electric current, cut a 4-inch length of magnet wire. To re-

move the insulating enamel, which can be burned off, hold each end in the flame of a match and then lightly scrape both ends clean with the edge of a knife, or with fine sandpaper. With one hand hold an end of the wire against the small metal cap on one end of a flashlight battery for 5 or 10 seconds, as in Fig. 1-1. With the other hand, feel the wire as it heats up.

Next, find a piece of paper-backed metal foil from a cigarette package. Cut a strip about 4 inches long and $\frac{1}{4}$ inch wide. Near the center, cut the strip down to $\frac{1}{32}$ inch wide, as in Fig. 1-2. Hold the metal side of the foil strip against the battery for 5 or 10 seconds as you did the wire. The result—which may surprise you—is caused by the tremendous agitation of the atoms in the thin, narrow part of the foil as billions upon billions of electrons are forced through it.

THE ELECTRIC CIRCUIT

Because, as we have seen, it is the movement of electrons which produces the heating or other desired effect of an

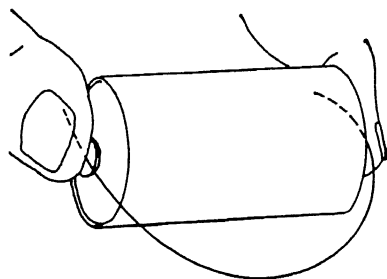


FIG. 1-1

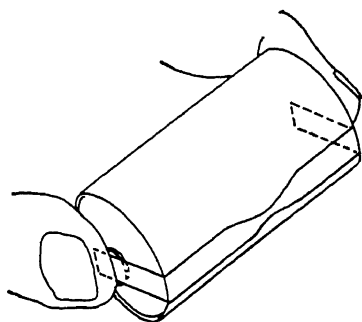


FIG. 1-2

electric current, some provision is required to keep the electrons moving in a continuous stream. If electrons are forced into one end of a piece of wire, electrons will be displaced down the wire until some of them reach the end. The electrons will go no farther, because air is an insulator. They will be crowded from behind by the oncoming electrons and will be squeezed closer and closer together until their accumulated force of repulsion allows no more electrons to enter the wire, and flow will stop. The whole process takes a tiny fraction of a second. Further flow can be produced by increasing the push from the source of electrons, but in an instant the flow will again stop.

What is needed to keep the electrons flowing is a *circuit*—a path for the electrons to get back to the source (the battery or generator), where they can either get another push around the loop or be absorbed.*

You can get a clear idea of an electric circuit by comparing it to a water system, as shown in Fig. 1-3. When the

* Throughout this book when we talk about the direction in which current flows we shall be talking about a current of *electrons*. Electrons flow from the negative terminal of the battery or other source around through the circuit to the positive terminal. Scientists knew a lot about electric circuits and batteries before they knew about electrons. Very early they found that they needed to talk about the direction of current flow and they arbitrarily said that current flowed from the positive terminal through the circuit to the negative terminal. This arbitrary, or *conventional*, direction of current flow is opposite to the direction of actual electron flow. In this book we shall always talk about electron flow. When you read other books, if they talk about direction of current it will mean the *conventional* direction unless they say *electron current*.

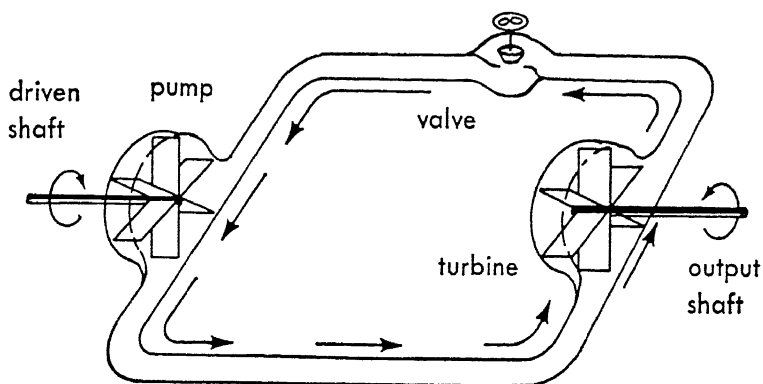


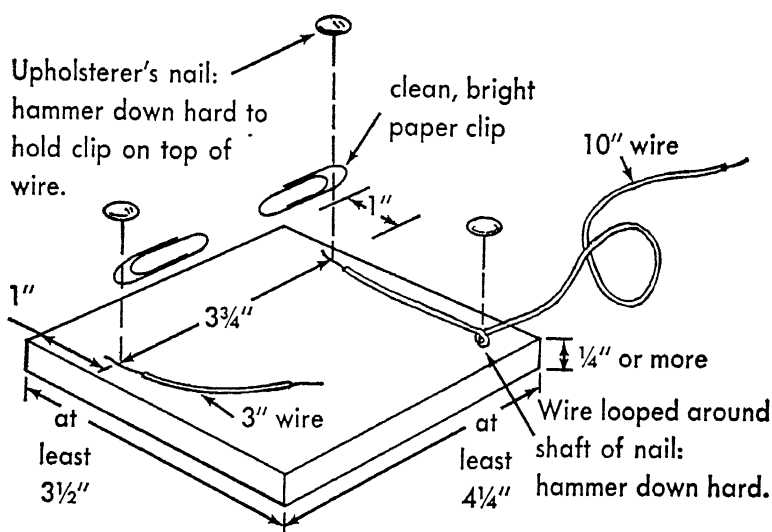
FIG. 1-3

pump is driven, water is forced around through the pipe to the turbine and then back through the valve to the pump for a second push. The turbine turns and can be put to work. But if the valve is shut—that is, if the circuit is broken—pressure will be built up in the line from the pump around through the turbine to the valve, but no flow will occur, and the turbine will not turn.

BUILDING A CONDUCTIVITY TESTER

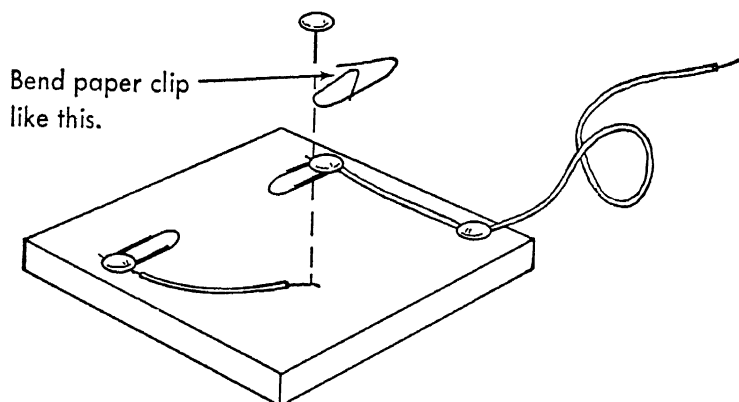
You can build an electric circuit that is very similar to this water system. It is called a conductivity tester, and it is a device used in every electronics laboratory and factory. You will be able to put it to good use for testing the conductivity of various substances and for testing circuits you will build later to make certain that they are connected correctly. Build it carefully, paying attention to every detail given in the directions.

If you have had experience in building things and in using tools, you may be able to make the conductivity



tester by carefully following Fig. 1-7. If you have not, Figs. 1-4 to 1-7 show you all the steps that must be followed.

First cut three lengths of bell wire, one 3, one 7, and one 10 inches long. Strip $\frac{1}{2}$ inch of insulation from each end of each wire. To do this, run a paring knife around the



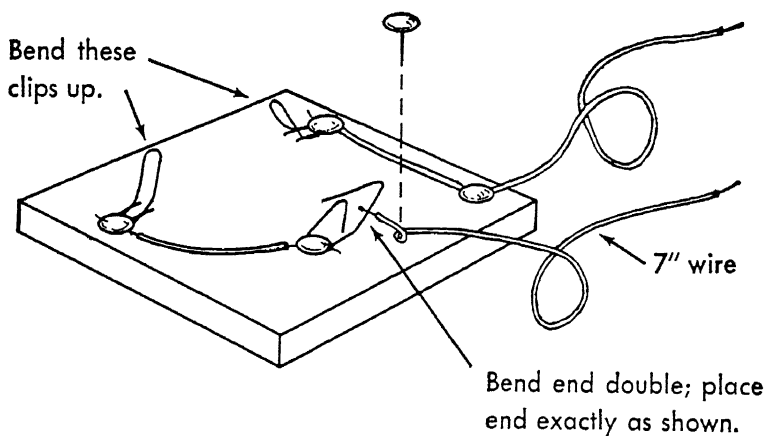


FIG. 1-6

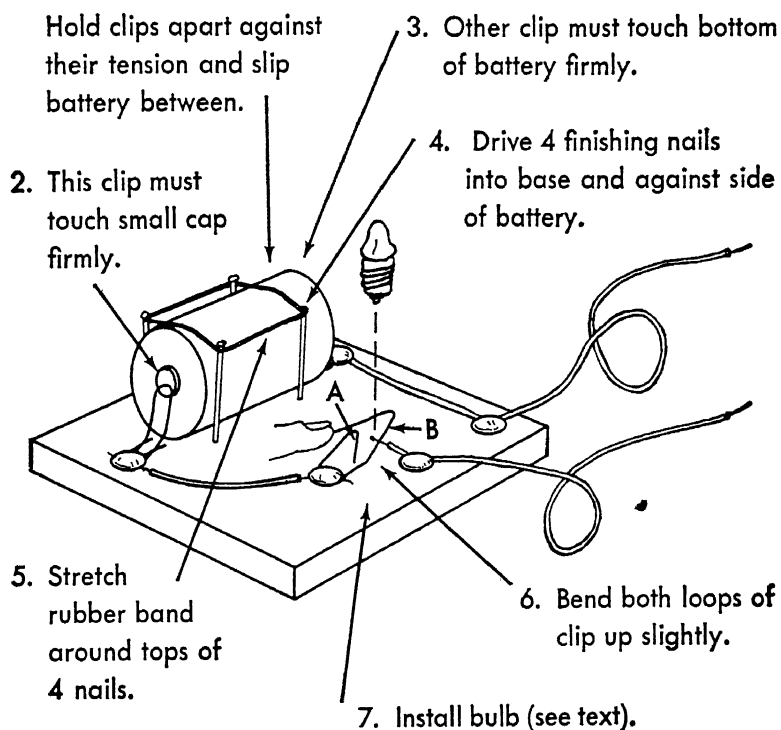


FIG. 1-7

MAKING ELECTRICITY WORK

insulation, being careful not to cut too deeply into the copper wire inside. Then slide off the insulation with the knife blade held against your thumb, as shown in Fig. 1-8. If the bare wire is not shiny, scrape it with the knife edge, because the dull oxide which forms on copper is a poor conductor.

Select a piece of wood for the base for the tester. It should be at least $4\frac{1}{4}$ by $3\frac{1}{2}$ inches, but it can be larger in either dimension. It should be wood which won't crack when you drive nails into it. (Upholsterer's nails have to be driven in with a hammer.) If you are in doubt, drive some nails into a sample near the edge where the grain ends. If the wood splits, stick the nail into a cake of soft soap before you drive it. Quarter-inch plywood is an excellent material for the base.

When installing the bulb, push the tip of the clip out and up, as in Fig. 1-7. Insert the bulb and release your finger so that the threads on the bulb are held between points *A* and *B*. Then lift the bulb by the glass and set the bent

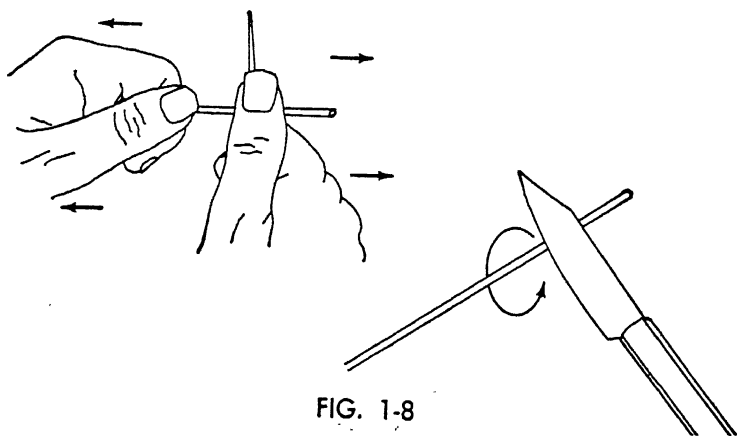


FIG. 1-8

end of the 7-inch wire under the shiny tip on the bottom of the bulb and let go.

When you have completed the conductivity tester, touch the two free ends of wire together. If you have followed the directions carefully, the bulb will light. Now if you touch the two ends to any substance, you can see whether it is a conductor or not. When you test a metal object, however, remember that rust and paint are good insulators and that you must therefore make contact with a clean, bright spot.

You can use the conductivity tester to demonstrate an important characteristic of conductors. Cut 6-foot lengths of hook-up wire and of magnet wire and clean the ends. Now test the conductivity of them both and of the 4-inch piece of magnet wire you prepared earlier. The bulb will glow less brightly with the long piece of magnet wire than with either the long piece of hook-up wire or the short piece of magnet wire. All three are copper. The longer and the finer a piece of conducting substance is, the greater resistance it presents to the flow of electrons. This explains why the paper-backed foil you tested earlier got hot enough to burn the paper at the point where it was thin and narrow. Whenever two substances are being compared for conductivity, comparison must be on the basis of the same length and cross section.

THE FLASHLIGHT BULB

The bulb in your conductivity tester lights up because a fine wire has a high resistance—that is, it gets hot when current flows through it. The part of the bulb which lights

up is a very thin wire of tungsten called the filament. It has to get very hot to give off light, and if there were air around it, it would burn to ash. To prevent this, the air is removed from the glass bulb. Even so, most metals would melt, but tungsten is used because it has a very high melting point. Tungsten also has a high electrical resistance compared to most metals, so the wire doesn't have to be as fine as if it were copper, for instance. If it were made *too* fine, however, it might break when the bulb is subjected to the mechanical shocks of normal use. The smallest practical size is about $\frac{1}{2000}$ of an inch in diameter ($\frac{1}{8}$ the diameter of a hair); and, at that size, to provide enough resistance to light properly, it must be almost an inch long. To get it into the bulb and to concentrate the light in one spot, the wire is wound into a fine coil. If you look at the bulb carefully under a magnifying glass you can see it.

The filament is supported on two heavy copper wires which bring the current in through the glass. One of these wires is connected to the threaded metal part of the base, and the other to the metal tip on the bottom of the bulb. It is through these two parts that you connected the bulb in the circuit. The tip and the metal threads are separated by an insulating material. You should by now be able to explain why that is necessary!

The battery and how it produces voltage are discussed in Chapter 3. But first you will want to build some useful circuits.

CHAPTER 2

CIRCUITS

The circuit of the conductivity tester which you constructed in the last chapter is, of course, the circuit of the ordinary flashlight. You used it as an indicator, but it can also be used for the light it gives off.

ILLUMINATING A DOLL HOUSE OR A MODEL TRUCK

Using a battery holder and bulb socket like those in the conductivity tester, you can install a light inside a model truck or a doll house. You can mount the components on a single base as you did before, or, to make them fit better inside the toy, you can divide them between two smaller bases. If you have mastered the mechanical and electrical principles involved in the design of the conductivity tester, you will be able to figure out in advance how you are going to mount the parts in the toy, and design the bases accordingly. Then from the positions you have decided on

for the parts, determine the lengths of the wire you will need for the connections.

If the doll house or truck is made of metal, you can use a part of its structure—the wall of the house, for example, or the body of the truck—to replace part or all of *one* of the wires in the circuit. This method of saving wire is called a *ground return* and is used in automobile wiring. Examine the truck or house to see how you can connect one terminal of the battery and one wire from the bulb to it. Since most paints are good insulators, you will have to clean the points at which you are going to connect the wire to the metal. Because current must be able to flow freely between the two points, test the conductivity between them with your tester.

You will also want to make a switch to turn the light on and off so that you won't have to twist and untwist the free ends of the wires. Follow the directions in Fig. 2-1. The wood base can be any size bigger than 1 by 2 inches and must be thick enough for the nails to hold. The exploded view shows how the parts are assembled, which is hard to see in the assembled view. Put a washer, then a clip, then another washer, and then another clip over the shaft of one upholsterer's nail and hammer it into the base. Line up the bottom clip as shown to act as a terminal for connecting the switch in the circuit. Put a clip over the shaft of another upholsterer's nail and drive it into the base an inch away from the center of the first nail. If the installation is going to be permanent, these last two terminal clips can be eliminated. Then the cleaned end of one wire from the circuit will go directly under the bottom

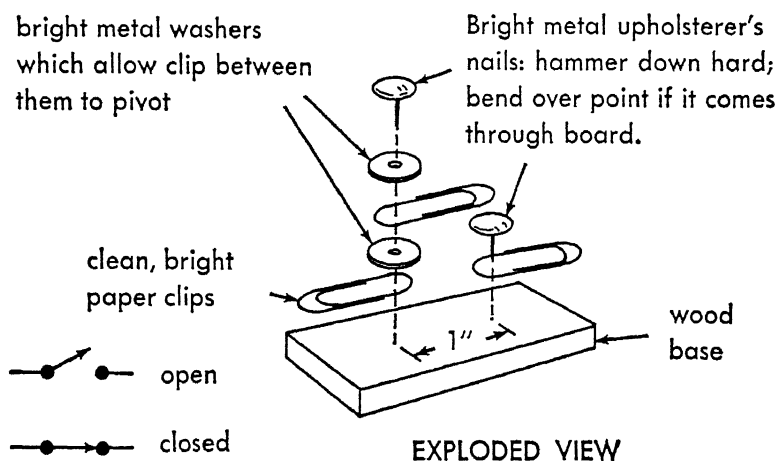
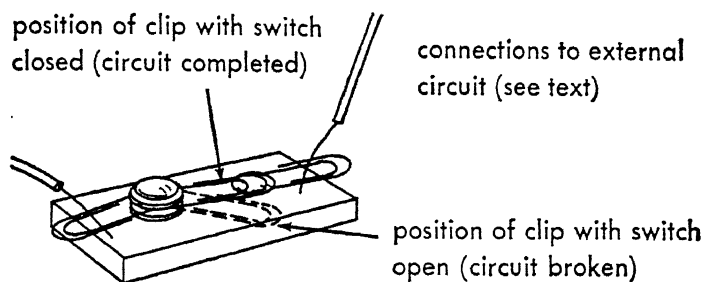


FIG. 2-1

washer when the nail is driven, and the end of the other wire will go under the head of the other nail. The clip between the washers on one nail can turn. In one position it will make contact with the other nail and complete the circuit in which it is connected. When turned away from the other nail it breaks the circuit.

MAKING ELECTRICITY WORK

Fig. 2-1 also shows a schematic symbol of the switch—a simplified picture that leaves out most of the details of the mechanical parts. The symbol is used in schematic diagrams like the one of the doll-house light in Fig. 2-2.

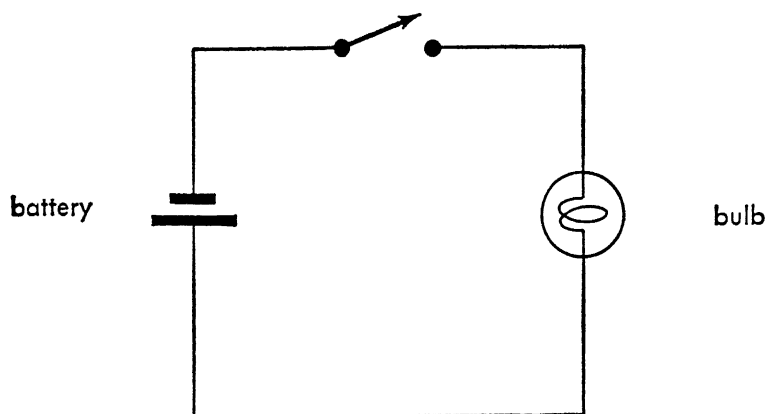


FIG. 2-2

There it is connected to a symbol for the battery and one for the bulb. The diagram shows the electric circuit without all the construction details, which may merely complicate it. You can see that it is also the schematic of the conductivity tester, in which the two wire leads are the switch, and of the ordinary flashlight, in which the “wires” are separate metal parts of the case.

CIRCUITS TO INDICATE “WHEN”

The conductivity tester indicates *whether or not* a substance is a conductor. You can use the same circuit in a number of ways to indicate *when* an action has taken place. Here are some projects—some of them games, some

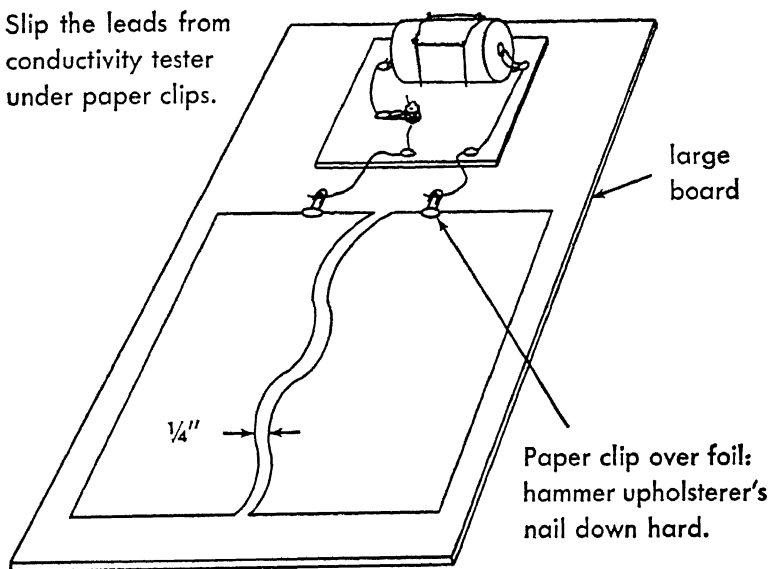
of them devices—in which the circuit is used to indicate *when*.

Penny Pitch

To make a game of penny pitch, follow the directions in Fig. 2-3. Each player must throw pennies from a fixed distance until he lights the bulb. You can see that *when* a penny touches both pieces of foil at the same time, it will close the circuit and light the bulb. The schematic

The conductivity tester: cover with colored paper.
Bulb should protrude through hole in paper.

Slip the leads from
conductivity tester
under paper clips.



Cut rectangle of kitchen aluminum foil down the center and paste two halves to board $\frac{1}{4}$ " apart.

FIG. 2-3

diagram is the same as that in Fig. 2-2, with the penny acting as the switch.

The game shown in Fig. 2-4 is designed to test how steady your hand is. The paper clip surrounds the wire, and if you are careful, you can run the wand from one end of the wire to the other without letting the paper clip touch the wire. But this isn't as easy as you think unless your hand is exceptionally steady. The bulb will light *when* the clip touches, so you and your friends can com-

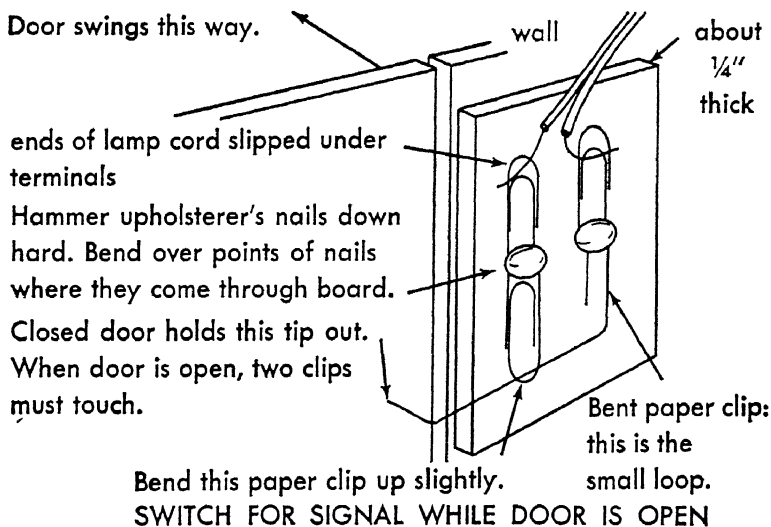


pete to see who can move the wand from end to end without lighting the bulb.

Burglar Alarm or Open-door or -drawer Indicator

The conductivity-tester circuit, in combination with a special switch, can also be used to indicate when a door or drawer has been opened.

Fig. 2-5 shows two switches. One keeps the light on



Strong black thread attached to door holds two clips apart until door pulls out thread.

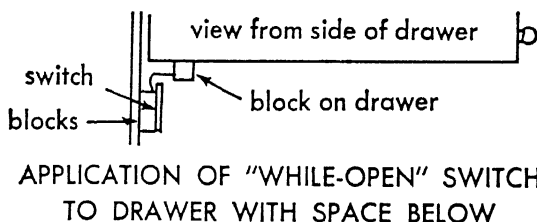
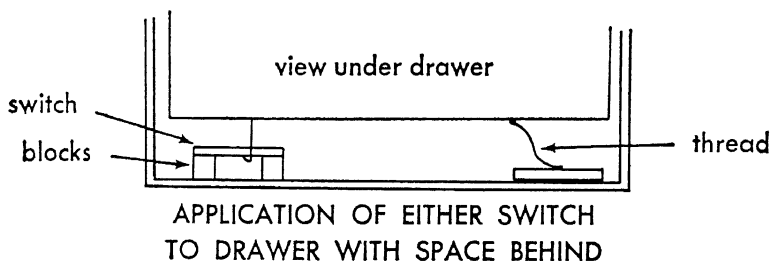
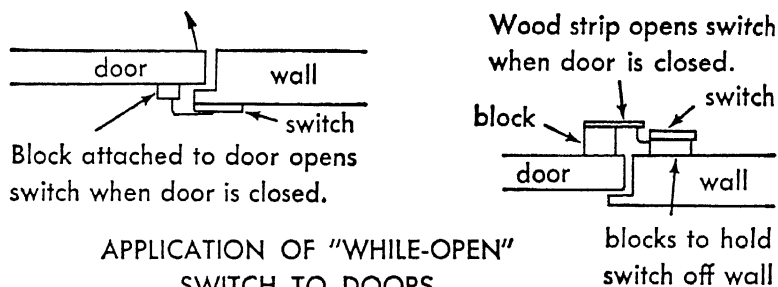
Bend up bottom clip slightly to make good contact with clip on top.

SWITCH FOR SIGNAL EVEN AFTER DOOR IS CLOSED AGAIN

FIG. 2-5

MAKING ELECTRICITY WORK

only while the door (or drawer) is open; the other lights when the door is opened and then stays on even if the door is closed again. Fig. 2-6 shows several methods of mounting which you can adapt to suit the details of your installation. You will probably want to mount the switch where it cannot easily be noticed. If you connect the free



Note: Get permission to attach switches to doors and furniture.

FIG. 2-6

ends of the wires on the conductivity tester (it will be the indicator) through a long pair of wires to the switch, you can locate the indicator in another room.

The best wire to use to connect the switch to the indicator (the conductivity tester) is two-wire lamp cord. It is a very good conductor, it is two wires combined into one cord, and it is flexible enough to run along the walls and under the doors from the switch to another room. Unlike the hook-up wire, which is one solid piece of copper, lamp cord is stranded—that is, it is made from many fine wires twisted together—to give it flexibility. Split it apart for a few inches at each end and remove $\frac{3}{4}$ inch of insulation. (With stranded wire you have to be careful not to cut into the copper and thus cut off too many strands.) Then in each wire twist the strands together tightly so that you can connect it as if it were one single strand. You probably won't have to scrape the wire to remove the oxide. The oxide usually forms on the outside of the outer strands only, and when you twist them together you bring a fresh surface to the outside.

To join the lamp cord to the leads of the conductivity tester, make a small separate terminal block like the one shown in Fig. 2-7. Slip one of the two wires at one end

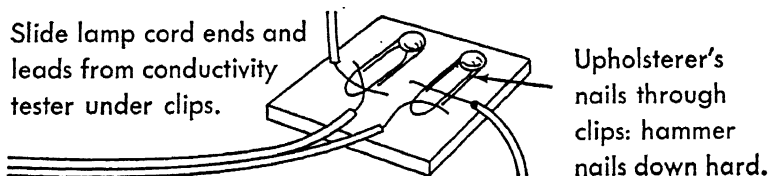


FIG. 2-7

MAKING ELECTRICITY WORK

of the lamp cord under each of the two terminals of the door switch, and run the lamp cord to the location you have chosen for the indicator. There slip one of the two wires under each of the two clips of the separate terminal block. Also slip one of the two leads of your conductivity tester under each of the clips of the separate terminal block. The circuit, starting from the base of the battery, is down one lead of the conductivity tester to one clip on the separate terminal block, then through one wire of the lamp cord (the one slipped under the same clip) to the switch, back through the other wire of the lamp cord to the second clip on the separate terminal block, through the second lead of the conductivity tester to the bulb, and from the base of the bulb back to the battery. Draw the schematic diagram of the circuit yourself. Then you will be sure you know how it works. It will be easy to disconnect the tester when you want it for other purposes.

Later, in Chapter 5, when you make a buzzer, you can use it as the indicator instead of a light.

VOLTS, AMPERES, AND OHMS

Up to now you have been learning about voltage, resistance, and current in only a general way; we have talked about insulators of *high* resistance, *low*-resistance metals that conduct *easily*, *heavy* currents, *more* push from the battery, *very* hot metal foil, etc. But the *amount* of any of the characteristics of electricity can be measured quite precisely in units, just as distance can be measured in miles or inches, milk in quarts, or wind velocity in miles per hour. The units by which electricity can be measured are

just as precise. Thus, whenever a scientist or engineer talks about a volt or an ohm or an ampere, every other scientist and engineer knows exactly *how much* he is talking about.

Volts

The voltage of a battery or generator is what forces current to flow in an electrical circuit, in the same way that the water pressure produced by the pump in Fig. 1-3 forces water to flow through the pipes. The units of water pressure are pounds per square inch, and the units of electrical pressure are volts. The flashlight batteries you have been working with produce an electrical pressure of about $1\frac{1}{2}$ volts. The voltage supplied at the wall plugs in your house is probably somewhere between 110 and 120 volts.

The greater the voltage applied to a circuit, the better insulation the wires need to prevent a short circuit, because more electrical pressure is being exerted. In the same way, thick pipes are required to carry water under high pressure. In automobiles the insulation is given rough use by rubbing against the frame of the automobile and by weather. One reason why automobile circuits are powered with only 6 or 12 volts is that so low a voltage presents less danger of short circuits.

Voltage can be measured with special instruments called voltmeters in the same way that your weight can be measured with scales and length can be measured with a ruler. For most practical purposes it is necessary to be able to measure voltage only within 5 or even 10%, and inexpensive voltmeters are adequate. When more accurate measurements are required—for instance, in the manufacture of

inexpensive voltmeters—carefully made, expensive voltmeters are used which can measure voltage to within 1% or better. These voltmeters lose their accuracy from the shocks of use and handling and have to be adjusted and calibrated from time to time. They are calibrated by comparing their readings with those of another accurate voltmeter which is carefully stored and handled and used only for this purpose. Such a voltmeter, or any other measuring instrument which is treated in this manner, is called a *secondary standard*. Even secondary-standard voltmeters are not accurate enough for some purposes—for instance, in the manufacture of secondary-standard voltmeters! For this reason some *primary standard* of voltage is required which will always be the same and which can be duplicated anywhere in the world by a scientist. As with all primary standards of measurement, the primary standard of voltage is accepted throughout the world as the basis of all voltage measurements. The primary standard of voltage which is used to check secondary-standard voltmeters is a very special type of battery, made from carefully selected parts and chemicals, which always produces 1.0186 volts when it is used under carefully controlled laboratory conditions.

Amperes

When voltage pushes a current of electrons through a circuit, the amount of current can be measured in electrons per second in the same way that the amount of water flowing out of a faucet is measured in gallons per minute. In your conductivity tester about 1,500,000,000,000,000,-

000 electrons pass through every second. Because so large a number is cumbersome, a more convenient unit called the *ampere* is used. One ampere is defined as 6,281,000,000,000,000,000 electrons per second.

When you turn on a 100-watt bulb in your house, the voltage from the wall plug pushes about 1 ampere through the bulb. An electric broiler or an iron is made so that the house voltage will push 10 to 12 amperes through it when it is in use. Look back at the number of electrons per second that flow when the conductivity tester is turned on, and at the number of electrons per second in an ampere, and you will see that very nearly $\frac{1}{4}$ ampere flows through the conductivity tester bulb.

You will remember that the more current that flows through a conductor, the hotter it will get. This applies to the wires that supply an appliance with current as well as to the conductors in the appliance. If the house wires carry excessive current they will heat their insulation so much that its insulating properties will be damaged and a short circuit will result. To keep the wires from carrying excessive current, fuses are needed. The fuse is inserted in the circuit, and all the current that flows through the wires must flow through the fuse. The active element of the fuse is a piece of special wire which will melt when the current exceeds a fixed amount, such as 15 or 30 amperes. When the fuse wire melts, it opens the circuit, of course, as if it were a switch.

The instrument used for measuring amperes is called an ammeter. As with voltmeters, there are inexpensive ammeters like the ones in automobiles which tell if the

battery is charging properly. And, of course, there are accurate ammeters and secondary-standard ammeters. The primary standard for amperes is a special laboratory setup involving electrochemistry, which you will learn about in the next chapter.

Ohms

When a definite number of volts is used to push current through a circuit, the number of amperes which flows depends on the resistance of the conductors that form the circuit. The *more* resistance there is in a circuit, the *fewer* amperes of current will flow with the same voltage applied. An electric iron designed to permit 12 amperes to flow when it is connected to 110 volts has much *less* resistance and produces much more heat than a 50-watt heating pad, which will allow only $\frac{1}{2}$ ampere to flow.

In order to express precisely how much resistance a circuit or circuit element has, we need a unit, just as we needed units for voltage and for current. The unit of resistance is the *ohm*. The electric iron has about 9 ohms resistance and the 100-watt bulb about 100 ohms. The bulb in the conductivity tester has about 6 ohms resistance.

There is an instrument—an ohmmeter—for measuring ohms, but resistance can also be measured with a voltmeter and an ammeter together, since 1 ohm is defined as the resistance which will allow 1 ampere to flow when the voltage pushing the current is 1 volt. As a matter of fact, an ohmmeter is simply an ammeter and a battery in one box arranged in such a way that when the fixed voltage of the battery is applied to an unknown resistance,

the ammeter will indicate the current that is allowed to flow. But instead of being marked in amperes, the ammeter dial is marked in ohms in accordance with Ohm's Law, which we shall discuss shortly. The primary standard for ohms is really the two standards for voltage and current.

Ohm's Law

Ohm, the man for whom the unit of resistance is named, discovered the fact which you now know—that the *more* voltage in a circuit of a given resistance the *more* current will flow, and the *more* resistance in a circuit of given voltage the *less* current will flow. He stated this fact in a symbolic equation as $I = E/R$, in which E is the number of volts, R is the number of ohms, and I is the number of amperes. You can see from your knowledge of fractions that if E doesn't change and R gets *bigger*, I will get *smaller*. You can also see that if R doesn't change and E gets *bigger*, I will get *bigger*. And, of course, these two statements agree with what you have learned about volts, amperes, and ohms.

Ohm's Law can be written $E = IR$ (IR simply means $I \times R$, but the multiplication sign is not used in this type of equation) and $E/I = R$ as well as $I = E/R$. These three forms of Ohm's Law are very useful in calculating ohms, or volts, or amperes for a circuit when two of these three values are known. Use your knowledge of simple arithmetic to see how $E = IR$ and $E/I = R$ are derived from $I = E/R$. Check these three forms of Ohm's Law against the values of voltage, resistance, and current occurring in

your conductivity tester. Remember that I in the conductivity tester is $\frac{1}{4}$ ampere, E is $1\frac{1}{2}$ volts, and R is 6 ohms.

Voltage Drop

The current in a circuit like that of the conductivity tester is the same in all parts of the circuit. If $\frac{1}{4}$ ampere flows through the bulb, then $\frac{1}{4}$ ampere must come out of the battery, $\frac{1}{4}$ ampere must flow in each wire, and $\frac{1}{4}$ ampere must go back into the battery. This is the same as the water system in Fig. 1-3. If 1 gallon per minute comes out of the pump, then 1 gallon per minute must pass through the pipes and the turbine.

When you checked the current, voltage, and resistance of the conductivity tester against Ohm's Law, you assumed that all of the resistance of the circuit was in the bulb. For practical purposes this is true, but the wires, and even the battery, have some resistance too. The wires have about $\frac{1}{25}$ ohm, and the battery has about $\frac{2}{5}$ ohm when it is new, which isn't very much compared to the 6 ohms of the bulb. Earlier you learned that a long wire has more resistance than a short wire of the same diameter. Since a long wire is simply several short wires connected end to end, you can see that resistances connected end to end, like the resistances in the conductivity tester, must be *added* together to get the total resistance of the circuit. In the conductivity tester the total resistance is about $6\frac{11}{25}$ ohms (the resistance of the bulb added to the resistance of the battery and of the wires). With $1\frac{1}{2}$ volts and $6\frac{11}{25}$ ohms the current is less than, but still very nearly, $\frac{1}{4}$ ampere.

Now look at the parts of the conductivity tester separately. In the wires there is $\frac{1}{4}$ ampere and $\frac{1}{25}$ ohm and Ohm's Law says $E = IR$. Hence $\frac{1}{100}$ volt of the $1\frac{1}{2}$ volts from the battery is lost as the current travels through the wire. Since the battery has $\frac{3}{10}$ ohm and $\frac{1}{4}$ ampere flowing in it, according to Ohm's Law $\frac{1}{10}$ volt of the original $1\frac{1}{2}$ volts is lost in what is called the *voltage drop* in the battery. The net result is that $1\frac{1}{2}$ volts minus the $\frac{1}{10}$ -volt drop in the battery and the $\frac{1}{100}$ -volt drop along the wires, or in other words $1\frac{3}{100}$ volts, is left for the bulb. The voltage supplied by the battery has divided itself among the resistances in the circuit.

This is why the bulb got dim when you tested poor conductors. When the resistance of the poor conductor was added to the resistances of the rest of the circuit, less current flowed—enough to make the bulb glow, but not very brightly. The current was the same in the bulb and in the poor conductor because only what got through one could get through the other. The voltage of the circuit divided largely between the bulb and the poor conductor, with a little going to the wires and the battery resistance. It was just as if the battery had been divided up into small pieces, each connected to a resistance of the circuit, each small piece being just the right size to produce the same amount of current in each of the resistances.

HOW CIRCUITS PERFORM WORK

When the bulb in the conductivity tester is giving off light, the circuit is doing work, in the same way that you do work when you lift an object, or a car does work when it is driven. The energy to do the work comes from

the battery, or your food, or the gasoline. The battery can do just so much work before it is used up, in the same way that you can clean one attic on a good meal or a car can go 15 miles on a gallon of gasoline.

The work that you want the conductivity tester to do is to give off light. It also does wasted work, because it gives off heat, which you know is produced when current flows through conductors like the bulb and the wires.

The conductivity tester has been designed to waste as little work as practical. Since the wires are fairly heavy copper, and therefore have much less resistance than the bulb, they produce very little wasted heat. They would waste less if they were heavier, but they would be harder to bend and would cost more. Because the bulb has to get hot enough to give off light, it has been designed to lose as little heat as possible. The filament has to be protected from oxygen to keep it from burning up. Just the oxygen could have been removed, leaving the nitrogen from the air inside the bulb, but the nitrogen would carry heat from the filament to the glass, where it would escape. With all the air removed from the bulb, the filament is insulated and loses much less heat, in the same way that the contents of a thermos bottle are insulated by the vacuum in the glass walls.

The conductivity tester can waste work in other ways. If you turn it on and don't look at it, all the work it does is wasted. You can say that a car gets 12 or 15 or 35 miles to a gallon of gasoline, but if you start the engine and leave it parked until it has used a gallon of gasoline, it will get zero miles to that gallon. And if you go 65 miles an

hour, you will waste work in making the tires hot and throwing up dust.

What Is a Watt?

Whether you drive your car at 20 miles an hour or at 40 miles an hour you will use about the same amount of gasoline to go a distance of 100 miles. The useful work—getting 100 miles away—will be the same in either case, but at 20 miles an hour it will take twice as long to do the work as at 40 miles an hour. At the two speeds, the same work is accomplished at different *rates*. Engineers call the rate at which a machine can do work the *power* of the machine, and the rate at which it is doing work at any time is the power it is developing at that time. A 1-horsepower gasoline engine can do work as fast—work as hard—as one horse. If the engine isn't running, it is still a 1-horsepower engine, and when running it can develop anything up to 1 horsepower, depending on how it is being used.

In electricity it isn't very logical to compare how fast a circuit does work to how fast a horse can do work. A unit of power—rate of doing work—is needed. The rate at which you move an object is how far it goes in a given time. The rate at which you *work* in moving an object is how *hard* you have to push *multiplied* by how far the object goes in a given time. The rate at which current flows in a circuit is measured in amperes—the number of electrons going by a point in a given time. The rate at which work is done in a circuit is the *voltage* or electrical push *multiplied* by the amperes flowing. The volts times

the amperes in a circuit is a new unit called the *watt*. When 1 ampere is pushed through a circuit by 1 volt, the rate at which work is being done—the power being developed—is 1 watt.

The symbolic equation for power is $P = EI$. Remembering that $\frac{1}{4}$ ampere is pushed through the conductivity tester by $1\frac{1}{2}$ volts, you can see that $\frac{3}{8}$ of a watt is developed. (A horse can do work 2000 times that fast, since 746 watts is equal to 1 horsepower.) A 60-watt bulb does the work of giving off light 160 times as fast as the conductivity tester, because $60 \text{ watts} \div \frac{3}{8} \text{ watts} = 160$.

If you apply Ohm's Law to the symbolic equation for power, you will be able to calculate power from resistance and current. Since $P = EI$ and $E = IR$, then P equals I times I times R , or $P = I^2R$. (I^2 simply means I times I .) Now you can calculate how much power is developed and wasted—how fast work is wasted—in the wires of the conductivity tester. Remember $\frac{1}{4}$ ampere flows through wires having $\frac{1}{25}$ ohm resistance—very little compared to the $\frac{3}{8}$ watt developed in the bulb.

Watt-hours

Power is the *rate* of doing work, but the important thing in life is *how much* work is done. If a farm hand can pitch 60 forks of hay per minute, he would be working at a terrific rate, but if he worked for only 1 second, only 1 fork of hay would get into the loft and the cows would complain. The number of substances you test for conductivity with the conductivity tester and what you learn from it is the really useful work of the conductivity tester.

But in terms of electrical work, the watts developed multiplied by the length of time the current is flowing equals the work produced by the conductivity tester. This idea suggests the electrical unit of work: the *watt-hour*. Watt-hours are calculated by multiplying the number of watts developed by the number of hours over which they are developed. If you left your conductivity tester turned on for 2 hours and 40 minutes it would do 1 watt-hour of work because $\frac{3}{8}$ watt $\times$ $2\frac{5}{6}$ hours = 1 watt-hour. This work is, of course, done by the battery, which can provide $\frac{3}{8}$ watt for about 16 hours, off and on, or 6 watt-hours of work, before it is used up.

If you used five 100-watt bulbs 5 hours a day for 30 days, you would use $5 \times 100 \times 5 \times 30$ or 75,000 watt-hours of electrical energy. Because this is an inconveniently large number, it is usually written 75 *kilowatt-hours*, which means 75 thousand-watt-hours.

The *amount* of electrical work is what you pay for. Your local power company charges you 4 or 5 cents a kilowatt-hour. If a dry cell supplies 6 watt-hours and costs 18 cents, how much are you paying for a kilowatt-hour? The price is very high, of course, but it is worth it because it wouldn't be practical to run a wire from your wall plug to your flashlight.

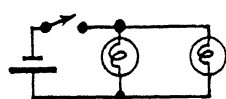
SERIES AND PARALLEL CIRCUITS

All the circuits you have worked with thus far have been a single loop consisting of battery, switch, and bulb connected by wire. The parts of the loop are said to be in *series*—that is, the current goes through first one, then

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another. When you were putting a light in a doll house, you may have thought it would be nice to install two lights, and perhaps you tried to add another bulb and socket in series with your original loop circuit. But if you were to put two bulbs in series, the voltage would divide between the two bulbs, half the voltage of the battery being across one bulb and half across the other, and they would light only dimly, if at all. But with two batteries and two bulbs in series, the double voltage of the two batteries would be divided across the double resistance of the two bulbs, giving each its normal $1\frac{1}{2}$ volts equal to that of one battery. With the two bulbs in series, if one burned out, the circuit would be broken and the other would go out. This happens in strings of cheap Christmas tree lights. Seven 16-volt bulbs are connected in series to 110 volts, because 16-volt bulbs are cheaper to make, and the wire for the string costs less.

An easier and better way of getting two bulbs working on the circuit is to connect the extra bulb and socket in *parallel* with the first, as in Fig. 2-8. In this way, the current does not go through one first, then through the other;



Connections in schematics
are shown like this.

to switch and
then battery

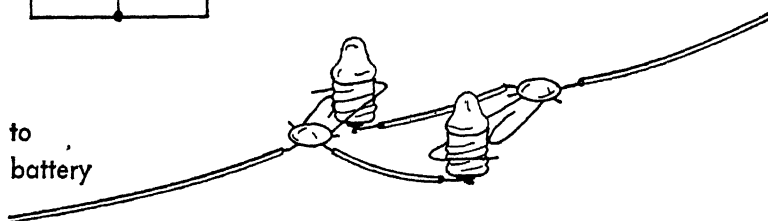


FIG. 2-8

instead it goes through both at the same time. If both bulbs have the same resistance—that is, if they are both designed for the same voltage and light output—the current will divide evenly between them. The resistance of the two bulbs in parallel will be half the resistance of each bulb, and the battery, therefore, will supply twice as much current. You can understand this easily if you remember that if a conductor is the same length and has twice the cross-sectional area of another conductor of the same substance, it will have half the resistance and draw twice the current of the second conductor. Now imagine the larger conductor split in half the long way with the two halves in parallel. You can see that it will still draw the same current as if it were one piece, and that half the electrons will flow down one side and half down the other. With two bulbs in parallel, the battery will be used up more than twice as fast, for reasons you will learn about in the next chapter.

The great economy of central power stations results from the consumer's being able to parallel two or more lights or other appliances across one voltage source. Each house can have lights, and a toaster, and a TV set, and a washing machine all operating independently in parallel from one pair of wires coming into the house. Then hundreds upon hundreds of houses can be paralleled across a huge generator, which can be operated efficiently and economically. The picture would be different if a separate source of voltage were required for each appliance.

In a parallel circuit you can have each bulb operated independently from its own switch by connecting them

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as in Fig. 2-9. You will notice that when both bulbs are on they will be dimmer than when only one is on. Can you reason why? Since $\frac{1}{4}$ ampere is flowing through each bulb, $\frac{1}{2}$ ampere is flowing through the battery when both

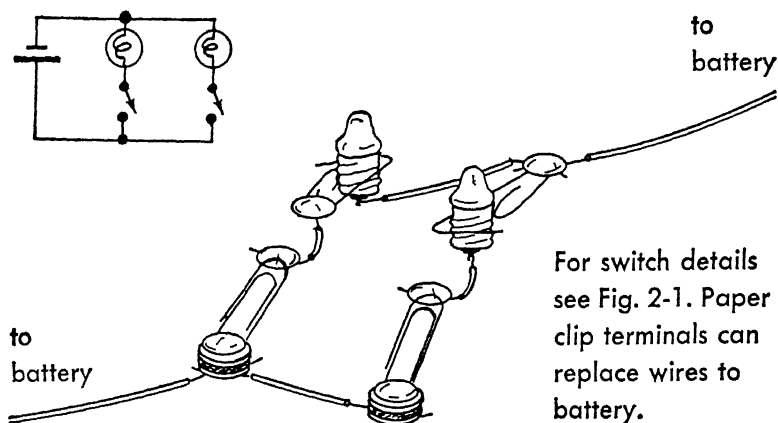


FIG. 2-9

bulbs are on and $\frac{1}{4}$ ampere when only one bulb is on. Since $\frac{1}{2}$ ampere flowing through the battery resistance will produce more voltage drop than $\frac{1}{4}$ ampere, there is less voltage for the bulbs when both are on.

MORE COMPLEX CIRCUITS

The single-loop series circuit can be quite useful for certain applications, as you have seen, and the simple paralleling of many appliances is essential for efficiency and economy, but many applications of electricity, such as computers, telephone systems, radios, and phonographs require complex combinations of both series and parallel

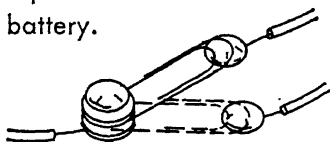
circuits. Not only will the following applications of series and parallel circuits introduce the complexities of electrical equipment but they are a lot of fun in themselves.

The Stair Light

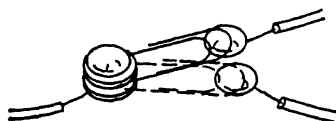
You have probably seen a stair light that could be turned on or off by a switch at the bottom of the stairs and another switch at the top, each one acting independently of the other. You can build a similar circuit and use it for a game of skill. You will need two two-position switches (also called single-pole double-throw switches) and your conductivity tester.

You can see from the schematic in Fig. 2-10 that with

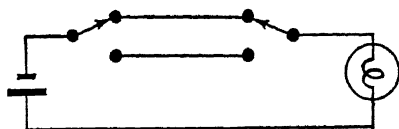
For switch details
see Fig. 2-1. Paper
clip terminals can
replace wires to
battery.



SWITCH A NONSHORTING



SWITCH B SHORTING



SCHEMATIC

bright metal upholsterer's
nails far enough apart so
clip never touches both at
the same time

bright metal upholsterer's
nails close enough together
so clip always touches one
or the other

FIG. 2-10

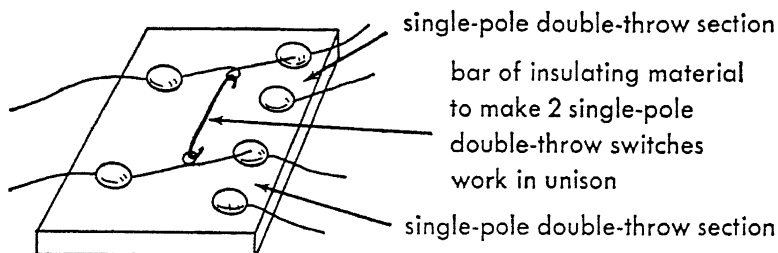
both switches up or with both down the circuit is complete, and with one up and one down the circuit is open. Hence the circuit can be opened or closed at any time by a change in the position of either switch.

To use this circuit in a game, connect it to your conductivity tester so that the bulb can be lighted or turned off from either switch. One player tries to keep the light on and the other tries to keep it off. If both switches are like Switch A in Fig. 2-10, the player trying to keep the light off could simply hold his switch between the contacts, and the bulb would never light. So he must use Switch B. On the other hand, the player trying to keep the light on could simply hold Switch B touching both contacts, so he must use Switch A.

Switch A is called a nonshorting, or break-before-make switch, and B is called a shorting, or make-before-break switch.

Arrange the wiring so that each player can see the light but cannot watch his opponent's handling of the switch. You may need a timekeeper to decide who wins—by keeping track of how long the light remains on during one minute.

A single light can also be operated independently from three or more switches—a useful arrangement where there are more than two doors into a room and you want to be able to control the lights from a switch on the wall at each door. Two of the switches may be single-pole double-throw switches as before, but the rest must be of a type called double-pole double-throw (or two-circuit two-position). This is simply two single-pole double-throw switches connected mechanically so that they operate in



SIMPLIFIED PICTORIAL OF
DOUBLE-POLE DOUBLE-THROW SWITCH

For 3 switches, A is wired to A and B to B.
For more than 4, switches are added like this.

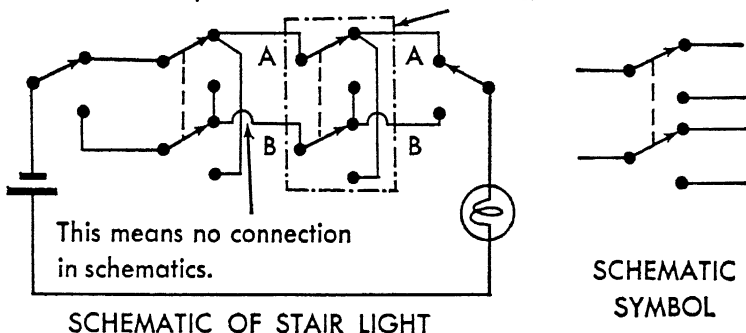


FIG. 2-11

unison, as in Fig. 2-11. Construction of such a switch will be illustrated later in this chapter (Fig. 2-13). Fig. 2-11 also shows how the stair-light circuit is wired for three or more switches.

Secret Voting Machine

You can build a voting machine which will light a bulb only when the members of a club are unanimously in favor of a motion. Make a switch like the one in Fig. 2-1 for each member of the club. Then wire them together as

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in Fig. 2-12. Each member holds a switch hidden in his lap. If you have more switches than members present, close the switches not in use. When a motion is made, those members in favor secretly close their switches. Unless all members close their switches the bulb will not light. If the bulb doesn't light, no one will know who was against the motion. Before voting, test by having everyone close his switch.

Computers

Most computers, or electronic brains, are extremely complex combinations of circuits which perform logical operations and arrive at conclusions. For example, they can carry out arithmetical processes, or solve equations, or

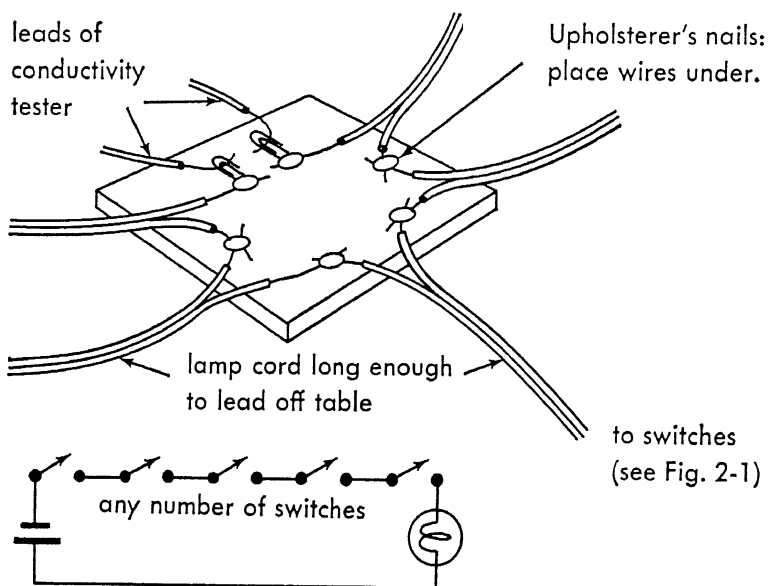


FIG. 2-12

draw conclusions from sets of conditions. Computers can be built to solve *specific* problems, such as determining how a gun should be pointed and when it should be fired in order to hit a target that is moving in a certain direction at a certain speed. Another specific problem might be how much of each of several kinds of grain should be mixed in an animal feed. The mix must be the lowest cost mix possible and still contain the advertised proportions of protein, carbohydrate, and fat, and it must be revised each day on the basis of the day's price for each grain. Computers can also be built to solve *general classes* of problems, such as a wide variety of accounting procedures. These machines must be temporarily wired, or *programmed*, to do any specific job. Computers use vacuum tubes and motors, and relays and keyboards, and many other electronic and electromechanical devices, but the logic that a computer uses to do its work is always *built into* its circuits. This means that the people who designed the computer must be able to solve the problem that the computer solves. You couldn't build a computer to solve the problem of the cheapest animal feed if you couldn't solve the problem yourself. But when it was built, it could solve the problem every morning in a few minutes on the basis of the day's prices of grain, and the answer would be ready before the mill was ready to mix the feed. The same problem might take a couple of hours with a pencil and paper.

The circuits used in that computer would be found arranged in different ways in many other computers. Here are some simple computers employing basic com-

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puter circuits and electrical components you have already learned about.

More-or-less Computer

You can build a more-or-less computer to test whether people are more or less athletic, more or less suited to space travel, or more or less anything else. This computer is of the simplest sort, but the more complicated computers used to solve very intricate problems consist essentially

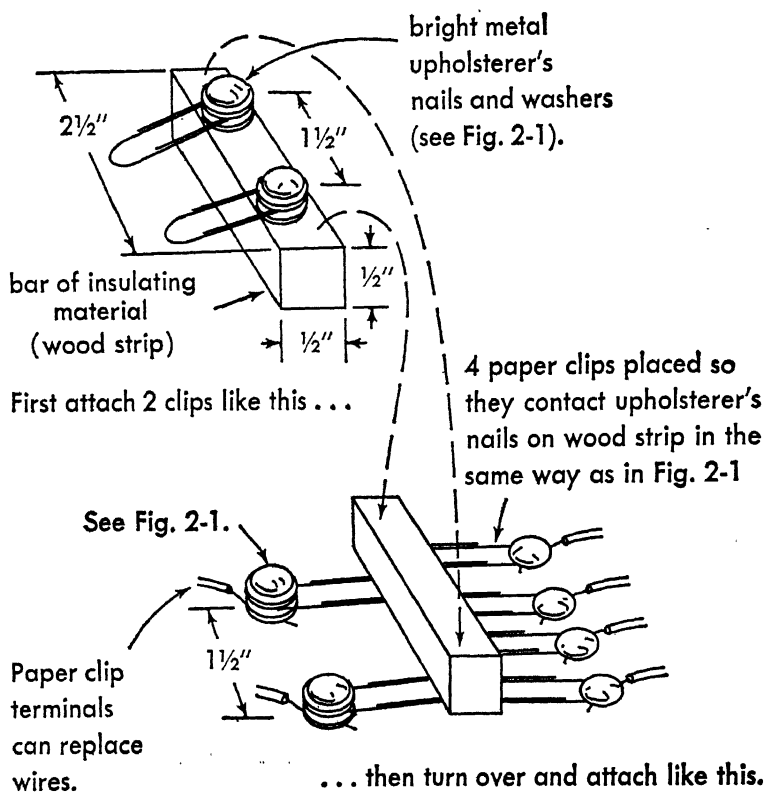


FIG. 2-13

of a great many variations of circuits like the one you are going to build. Once you understand this circuit, you will understand the techniques involved in using the giant computers, even though you have neither the advanced technical skill nor the very refined components with which to build one.

You will need six switches of four different types. Two will be single-pole double-throw (SPDT) switches like the one in Fig. 2-10. Two will be double-pole double-throw (DPDT) switches like the one illustrated in Fig. 2-11. Construction details for these switches are given in Fig. 2-13. One switch will be a three-pole double-throw or three-circuit two-position (3PDT) switch. It is made by extending the principles of Figs. 2-11 and 2-13 to make three single-pole double-throw switches joined together so that they operate in unison. The remaining one will be a push, or momentary-contact, switch which conducts only while you hold it down. Its construction is shown in Fig. 2-14.

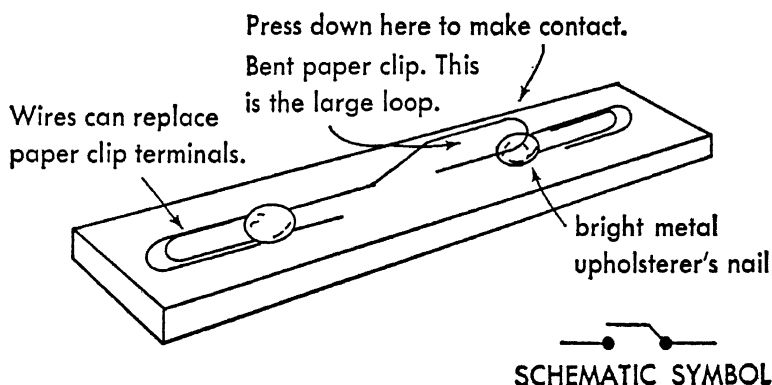


FIG. 2-14

The computer scores an examination like this:

ARE YOU MORE OR LESS SUITED
TO SPACE TRAVEL?

1. Do you like to be with groups of people, rather than by yourself?
2. Do you prefer the wide-open spaces?
3. Do you like simple, nourishing food?
4. Do you prefer baseball to a tramp in the woods?
5. Do you get good marks in mathematics?

A "no" answer to the first and fourth questions and a "yes" answer to the second, third, and fifth questions would all indicate more, rather than less, suitability for space travel. The computer must be designed to flash "more" when at least three of the five answers indicate more. The schematic in Fig. 2-15 shows how the computer is designed to do this. If the first three questions have "more" answers—that is, if the first question is answered "no" and the second and third are answered "yes"—the circuit will be completed to the "more" bulb, which will light when the "result" switch is pressed. No position of the fourth or fifth switch can affect this result. They cannot feed current to the "less" bulb nor can they break the circuit to the "more" bulb. If the answer to any one of the first three questions indicated "less"—for example if the first question were answered "yes"—then the fourth switch would come into play. If it were set to indicate "more,"—that is, if the fourth question were answered "no"—the score would again be three "more's," and the circuit would again be completed to the "more" bulb.

Go through Fig. 2-15 step by step and see for each

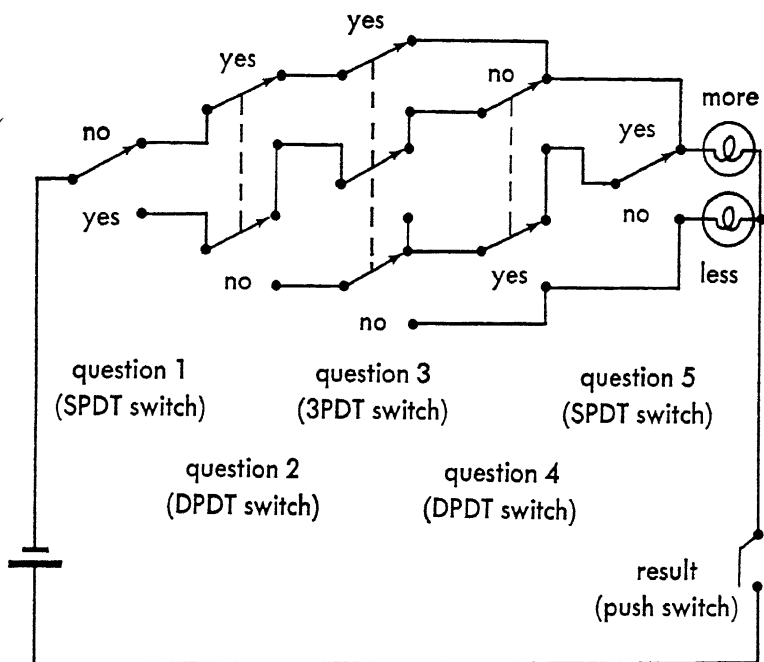


FIG. 2-15

position of each switch how the circuit is completed to either the “more” or the “less” bulb. Tally each result against the questions in the examination. Three or more “more” answers always light the “more” bulb, and three or more “less” answers always light the “less” bulb.

You can see that if the examination were reworded to have “yes” answers always indicate “more,” the computer would give away its logic and the person being examined could tailor his answers to give the result he wanted to get. The push switch prevents either bulb from lighting while the switches are being set, which might also give away the logic.

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To further protect the computer's secrets, the "yes" position of the five switches must be in the same physical direction. The revised schematic in Fig. 2-16 shows the first and fourth switches rearranged to achieve this. The circuit is identical with that of the schematic in Fig. 2-15, but some of the wires are rearranged. Examine the revised schematic carefully to see how to wire the computer. The bulb sockets and battery holder are the same as the ones you have made previously.

Make up additional examinations on other subjects. Be sure to observe the relationship of "yes" to "more" answers as built into the computer.

Perhaps you are wondering why it was necessary to

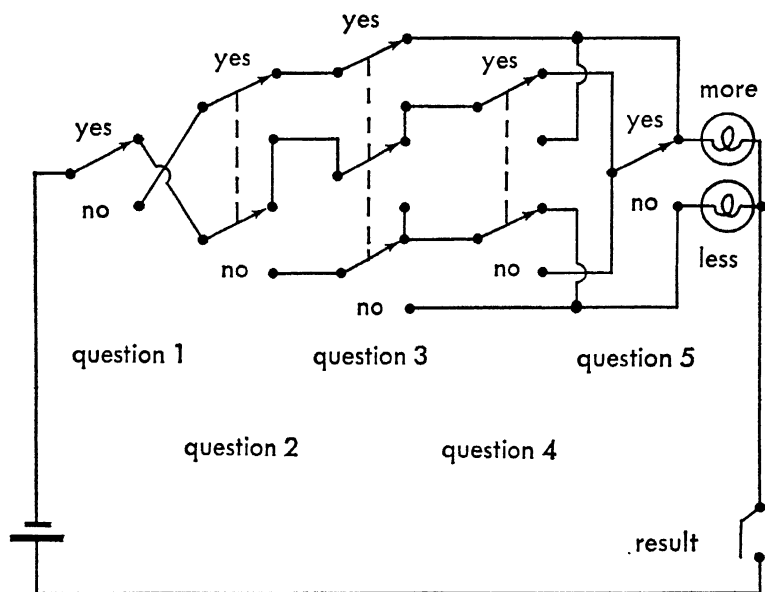


FIG. 2-16

build this computer in order to get the results of a series of questions that could easily be scored "by hand." The answer is that you were building it in order to understand its principles rather than to save time in scoring the questions. But actually you do save time in scoring the questions, because the result is available to you the instant that the last question is answered, and there is no need for you to score the answers afterward.

The circuit in Fig. 2-15 can be used as a secret voting machine to tell when a *majority* of voters is in favor of a motion. The up position (in Fig. 2-15) of each switch must be labeled "for," and the down position "against." The "more" bulb must be labeled "passed" and the "less" bulb "defeated." The circuit works for five voters, but three can vote if one unused switch is set at "for" and the other at "against" and the other three are used for voting. By tracing the schematic and examining the logic you can see what would happen if there were four voters or if one of the voters did not close his switch either way.

See if you can figure out what additional switches and what wiring additions would be required to make the machine work for seven voters. You will have to discover the pattern in Fig. 2-15 and extend the principles which you have learned about the design.

The Game of Black Match

Computer engineers like to design and program computers to play games. Of course, such games are fun, but they also have a very serious purpose. The engineers want

to be able to design new computers to solve more and more complicated problems in science and business with less and less help from people. A computer can do more for itself if it is designed with circuits in it that can figure out which operations it should perform to solve a problem. Game playing helps computer engineers to learn how to build such circuits. A computer has been programmed to play chess, but in spite of its huge computing capacity it plays a dull game and is easily beaten by all but beginners. On the other hand, one of the IBM office computers has been programmed to play checkers. Since checkers is a simpler game than chess, the engineers were able to program it to remember every game it ever played, and although it can be beaten, it can never be beaten the same way twice. This is a machine that can learn by experience, but it does it by logical processes built, or programmed, into its circuits.

You can build a computer to play the game of black match against your friends. This game is played with a pile of 22 to 25 matches, one of which is black. Two players in turn pull the matches out of the pile, taking from one to four at each turn. Each player's object is to pick up matches in such a way that at the end only the black match remains for his opponent to take.

First you had better take 25 matches or other markers and play a sample game against yourself, because you must understand the game and the logic for winning before you can understand how a computer can play the game and win. In the sample, your left hand plays against your right as follows:

| LEFT HAND
TAKES | LEFT HAND
LEAVES | RIGHT HAND
TAKES | RIGHT HAND
LEAVES |
|--------------------|---------------------|---------------------|----------------------|
| 4 | 21 | 1 | 20 |
| 1 | 19 | 3 | 16 |
| 2 | 14 | 3 | 11 |
| 3 | 8 | 2 | 6 |
| 2 | 4 | 3 | 1 |
| 1 | 0 | | |

Your right hand won because your left hand was forced to take the last match. It was forced to because your right hand followed the logic for winning.

Here is how the logic works starting from the end of the game:

| | | | |
|-------------------------|----------|-------------------|-----|
| If the one who | | he can | |
| knows the logic | | be sure of | |
| is faced with | 2 to 5 | leaving | 1* |
| “ | 7 to 10 | “ | 6* |
| “ | 12 to 15 | “ | 11* |
| “ | 17 to 20 | “ | 16* |
| “ | 22 to 25 | “ | 21* |

* because he may take 1, 2, 3, or 4.

| | | | |
|------------------|----|--------------------|------------------|
| If he | | he can | |
| leaves | 1 | be sure of | winning* |
| “ | 6 | “ | facing 2 to 5* |
| “ | 11 | “ | facing 7 to 10* |
| “ | 16 | “ | facing 12 to 15* |
| “ | 21 | “ | facing 17 to 20* |

* because his opponent must take 1, 2, 3, or 4.

MAKING ELECTRICITY WORK

Now look back at the sample game to see how your right hand won. In its first turn it couldn't leave 21 because it was faced with 21 and it must take at least 1 according to the rules of the game. So it took 1, leaving 20 in order to have the best possible chance of leaving 16 in its next turn. At the moment your left hand took 1, leaving 19, it lost the game because your right hand could now leave 16 with absolute assurance of being able to leave 11 on the next turn, 6 on the next and the winning 1 on the last. There was nothing your left hand could do to prevent this once it had left 19. Had it left 16, it could have been the winner, of course. If your right hand had started the game, it could have left 21 the first time and only a mistake on its part would permit your left hand to win.

Your computer will always win if it plays first and will always win if it plays second provided its opponent makes one mistake, because the logic for winning will be built into its circuits.

The construction of the computer is shown in Figs. 2-17 and 2-18 and the schematic in Fig. 2-19. First you will need to know how the circuits are designed to play the game so you won't make mistakes in building it. The points of the 25 upholsterer's nails in the front view represent the 25 matches. Each nail is connected to a bulb marked 1, 2, 3, or 4, representing the computer's choice. If there are 25 in the pile, the computer must take 4 to leave 21, and therefore the nail marked 25 is connected to the bulb marked 4. If it has been decided to play the game with 25 matches (instead of 24, 23, or 22 as allowed by the rules) and if it is decided that the computer shall

NUMBER OF
MATCHES LEFT
IN PILE

BLACK MATCH COMPUTER

Place rules here.

For bulb sockets see Figs. 1-5 to 1-7.

COMPUTER'S CHOICE

Same holes
as in back
view.

bulbs and
sockets

For details of
push switch
see Fig. 2-14.

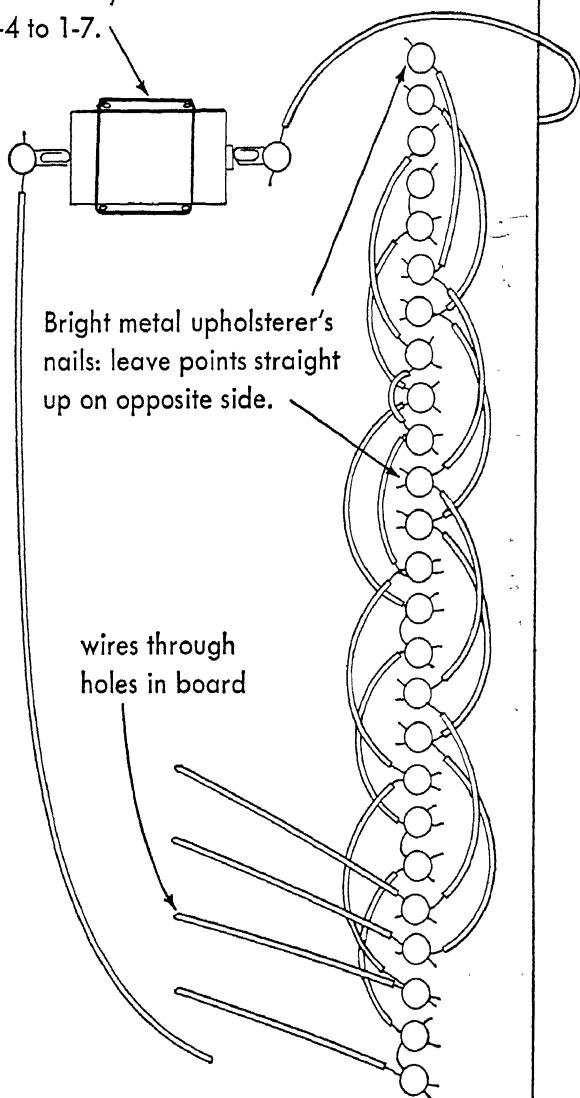
THE BLACK MATCH

1/4" board

FRONT

FIG. 2-17

For details of battery holder
see Figs. 1-4 to 1-7.



BACK

FIG. 2-18

start, then the computer's operator touches the free wire to the point of the nail marked 25 and presses the push switch. Current flows from the battery through the free wire to the point of the nail marked 25, through the nail to the wire under its head, and through the series of wires to the tip of the bulb marked 4. From the bulb it goes through the wire connected to the threaded parts of all 4 bulbs to the push switch and back to the battery. Voltage can't get to the tips of the other 3 bulbs to light them. With the bulb marked 4 lit, the computer's operator subtracts 4 from 25 and gets 21. He then releases the push switch and allows the opponent to select 1 to 4 matches. He subtracts the opponent's choice, say 3, from 21, getting 18. He moves the free end of the wire to the nail point marked 18 and presses the push switch. This time the bulb marked 2 lights. Trace out the wiring on the back view and the schematic to see why. All the other nail

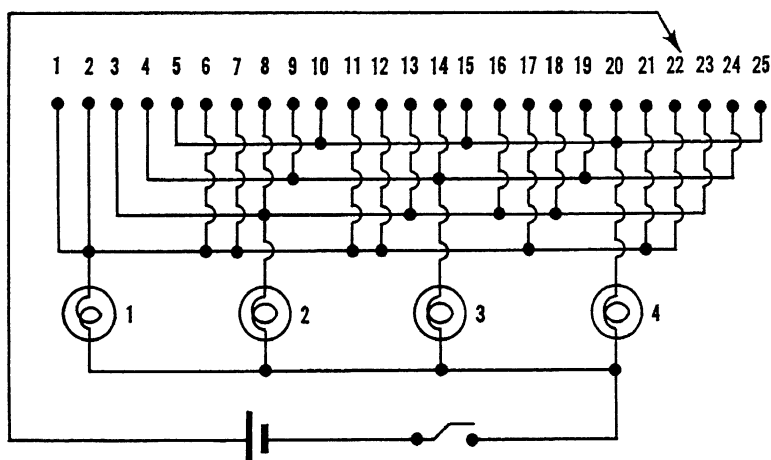


FIG. 2-19

points except 1, 6, 11, 16, and 21 are wired to light the difference between their number and 1, 6, 11, 16, or 21.

If the opponent starts and his choices leave 21, 11, or 6 in the pile, the computer takes 1—that is, the computer is wired to light the bulb marked 1—to give its opponent the best chance for error. It should take 1 if it is left with 16, but instead it takes 2 to help hide its logic. When the computer is left with 1, it lights the bulb marked 1, to show that it knows it's beaten.

In building the computer, start with a board at least 7 by 14 inches. It should be $\frac{1}{4}$ inch thick so it will be strong but thin enough for the points of the 25 upholsterer's nails to come through. Quarter-inch plywood is best. Use upholsterer's nails with conducting metal heads. Hammer 25 of them in *almost* all the way in a row, and at least $\frac{1}{2}$ inch apart. Then start cutting and stripping the ends of bell wire to connect the heads of the nails as shown. When all the free ends are under each head, drive the nail down hard. Wires between adjacent nails don't need insulation. The bulb sockets and battery holder are just like the ones in your conductivity tester, so see Figs. 1-4 through 1-7 for the details. The push switch is just like the one in Fig. 2-14.

Mark the front of the board with all the lettering and numbers shown. Copy out the following rules and paste them on the front of the computer:

1. Decide if you want to start with 22, 23, 24, or 25 matches, and hold the pointer against that number.
2. If *you* want to start, move the pointer down 1 to 4 numbers—to indicate the number of matches you are

taking—and hold it there. You must take at least 1 but not more than 4 matches.

3. If you want the *computer* to start, and for the computer's subsequent turns, hold the pointer where it was and press the "computer's choice" switch to see how many matches the computer has decided to take.

4. Release the switch, and move the pointer down as many numbers as the computer chose.

5. Reduce the number in the pile by your next choice, and continue in this manner until you or the computer loses by being left with only the last match to take.

Now that you know the logic, there isn't much point in your playing against the computer; you will always win if you start and the computer will always win if you let it start. But you and your computer can beat your friends until they make you explain the principles to them.

CHAPTER 3

WHERE ELECTRONS COME FROM

Thus far we have been working with a current of electrons flowing through conductors and through circuits made up of conductors. In each case we used a battery which produced our stream of electrons, or—to look at it in another way—which converted the energy of chemical reactions into electrical energy. In this chapter you will get a basic understanding of the chemistry of electricity and thus learn how chemicals can be used to produce a current of electrons and also how a current of electrons can be used to produce chemical reactions. The explanations will have to be followed very carefully, because they involve the complexities of atomic structure, but after you have made your own battery you will understand one of the most important methods of making and storing electricity.

Every chemical reaction involves electrically charged particles. Many chemical reactions can produce electricity, and many other chemical reactions can be made to take place by a flow of current. The storage battery in an automobile works by a chemical reaction. Metals are purified, chemicals are manufactured, cheap materials are plated with thin coatings of gold and silver, and many other useful results are obtained through electrochemical means.

HOW CHEMICAL ELEMENTS COMBINE

To understand how a battery works, you will need to review some things you may already know about chemistry. You will remember from Chapter 1 that the nucleus of each different basic substance, or element, has a different fixed number of positive charges and therefore attracts a different number of electrons. It is this number of electrons (negative) that its nucleus can attract by electrical charge which gives the atom of each element its distinctive chemical characteristics, or, in other words, makes it a different substance.

When the nucleus of an atom has all of the electrons around it that it can attract by its positive charge, it is said to be in its normal or electrically neutral state. The charges are still there, but each positive charge on the nucleus is balanced, or neutralized, by the negative charge of 1 electron. Hydrogen, the simplest chemical element, has only 1 electron in its electrically neutral state. Helium, a light gas used in balloons, has 2. Oxygen, which combines with hydrogen to form water, has 8 electrons

in orbits about its nucleus when it is in its electrically neutral state. Sodium, a metal that is chemically very active, has 11 electrons. Chlorine, a gas that combines with sodium to form table salt, has 17. In between there are elements that have 3, 4, 5, 6, 7, 9, 10, 12, 13, 14, 15, and 16 electrons. There is a natural element for each number of electrons up to 92, and elements having even more electrons have been produced by cyclotrons and other means.

Electron Patterns

The electrons are arranged around the nucleus of the atom in shells or layers called rings. The ring nearest the nucleus always consists of 2 electrons, except in hydrogen, which only has 1 electron. The outermost ring always consists of 8 or fewer electrons. Rings between the inner and outermost ring can contain up to 32 electrons. Fig. 3-1 is a suggestion of what an atom of oxygen might look like if you could see it. Actually, of course, nobody knows what the oxygen atom, or any other atom, looks like, but in all its chemical and electrical reactions oxygen *acts* as if it looked like the pictorial suggestion. Throughout this chapter, atoms will be illustrated in schematic drawings. Schematic drawings of electrical circuits, which you have seen in Chapter 2, are simplified pictures of the circuits, and schematic drawings of atoms are simplified pictures of the atoms showing the charge on the nucleus and the arrangement of the electrons in the rings. Below the pictorial suggestions of the oxygen atom are

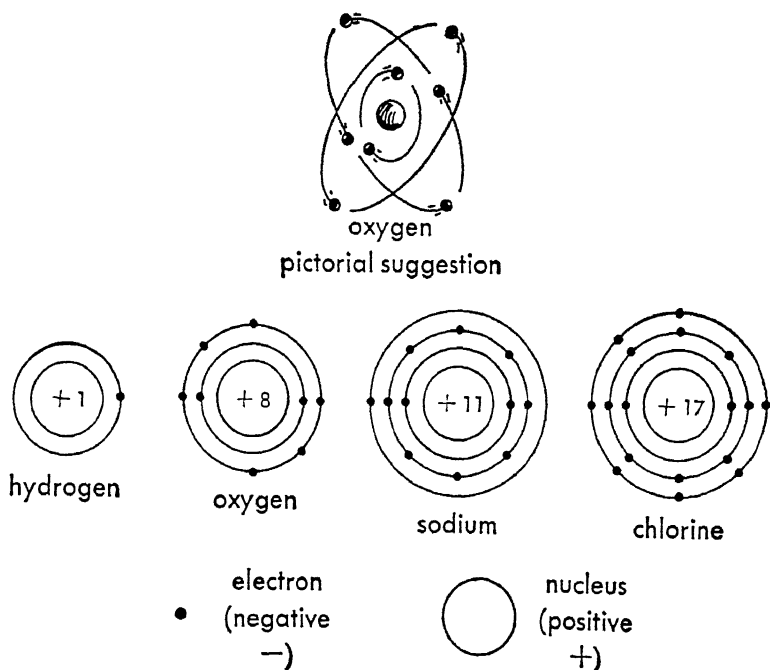


FIG. 3-1

schematic drawings of atoms of hydrogen, oxygen, sodium, and chlorine.

It is the outermost ring that determines the way an element reacts chemically. For some obscure reason there is a tendency for an atom to complete its outer ring to 8 electrons—or 2 in the single case of hydrogen. This tendency has nothing to do with electrical charge but seems to depend on some natural tendency toward symmetry. If the neutral atom (one with as many electrons in orbit as there are positive charges on its nucleus) has 8 electrons in its outermost ring, or 2 in the single case of helium, it is chemically inert—that is, it will combine with other

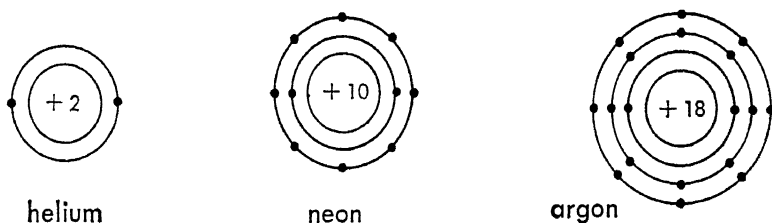
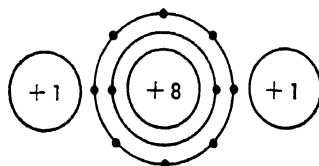


FIG. 3-2

elements only under the rarest conditions. Fig. 3-2 shows schematic pictures of atoms of three inert elements: helium, neon, and argon.

In other elements, the tendency to complete the outermost ring determines the kind of chemical combinations the element will form. For example, an atom of oxygen and 2 atoms of hydrogen combine to form what is called a molecule of water. Here's why. Oxygen, with 6 electrons in its outermost ring, needs 2 more to complete the ring to 8. When water is formed, 2 hydrogen atoms give up an electron each to an oxygen atom, completing its outer ring to 8. In the water molecule, oxygen has 2 negative charges because it has a total of 10 electrons and only 8 positive charges on its nucleus. The two hydrogen atoms, each now lacking an electron, together have two positive charges and are attracted to the negatively charged



water molecule

FIG. 3-3

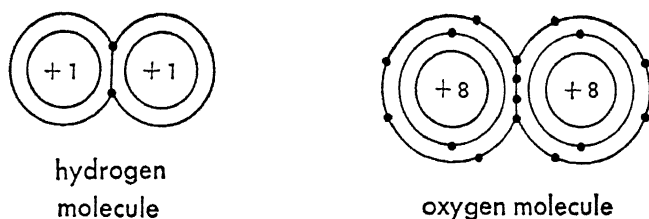


FIG. 3-4

oxygen. The molecule is neutral because it contains equal numbers of electrons and positive charges. Fig. 3-3 is a schematic of the water molecule.

Hydrogen and oxygen do not combine simply because they are mixed together. Hydrogen and oxygen as separate neutral atoms—which they rarely are, as we shall see in a moment—are very active chemically. This means that they combine readily with atoms of other elements, *including themselves*. Two hydrogen atoms almost always form a hydrogen molecule in which each shares the other's electron, so that they each have an outer ring of 2 electrons, as in Fig. 3-4. The hold that the two atoms have on each other, called the *bond*, is weak, but it does reduce the chemical activity of the individual hydrogen atoms, because the bond must be broken before the hydrogen can combine with other elements. The same is true of oxygen; 2 atoms form a molecule of oxygen with 4 shared electrons completing both outer rings of 8, as in Fig. 3-4.

Release of Energy

Whenever chemical elements combine, energy is either released or absorbed. When hydrogen and oxygen mole-

cules are mixed, it takes something like a spark or flame to break the molecular bonds. Then the atoms rearrange themselves into water molecules, two atoms of hydrogen to one of oxygen. The combining process releases energy in the form of heat, which breaks the bonds of more gas molecules, and the process continues until all of either the hydrogen or the oxygen has been combined into water. The release of heat energy can be so rapid and violent that an explosion occurs. When you light an oven, for example, you must hold the lighted match to the jets before you turn on the gas. Otherwise the gas, which contains hydrogen and similar gases, will mix with oxygen from the air in the oven, and if you then put in the match you can be burned by the explosion.

A good deal of energy (in the form of heat, together with some light and even sound) is released when hydrogen and oxygen combine into water, and therefore a good deal of energy must be supplied to separate them. This is another way of saying that the molecular bonds of water are strong.

HYDROLYSIS

The molecular bonds of water can be broken to separate it into hydrogen and oxygen by means of a current of electricity. To do this an electrolytic cell—one of many possible types—is required (see Fig. 3-5). All cells consist of two conductors, called the electrodes, immersed in a liquid, called the electrolyte. Don't try to make a cell for breaking up water yourself, because the lye required in the water—like many other useful chemicals—can burn

Hydrogen displaces electrolyte and collects here.

Glasses filled under water and turned upside down remain filled.

Oxygen collects here.

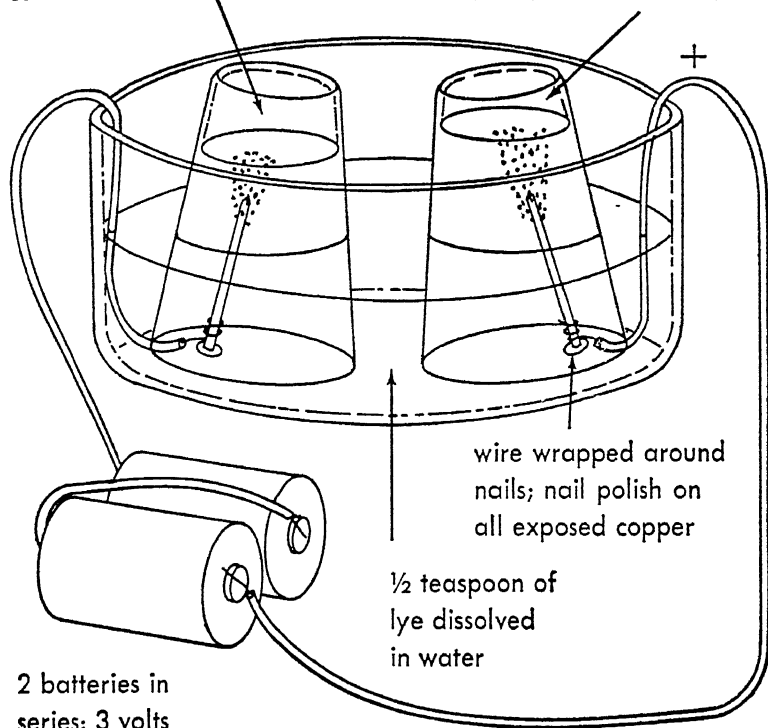


FIG. 3-5

you and your clothing and can even blind you. You might ask an adult—teacher or parent—to help you make one. He can provide the lye and supervise your use of it. Even if you don't make one, however, the explanation that follows will prepare you to understand the battery.

First let us see how the cell would work if it contained only water. Then we shall see how it works when it contains lye dissolved in water as shown in the figure. When

MAKING ELECTRICITY WORK

current is flowing to the cell, oxygen is formed at the electrode connected to the positive terminal of the battery, and hydrogen at the electrode connected to the negative terminal. The reason for this is that in all water, even though the bond between hydrogen and oxygen is quite strong, a very few molecules break apart spontaneously. When they do, the oxygen atom keeps one hydrogen atom and the electron it borrowed from the other, so that its outer ring retains the complete shell of eight electrons. The hydrogen atom which came off without its electron, as in Fig. 3-6, has a positive charge and in this charged condition is called a hydrogen *ion*. The remaining oxygen-hydrogen combination is called a hydroxyl ion, and it has a negative charge because it has an extra electron.

At the negative electrode of the cell, hydrogen ions

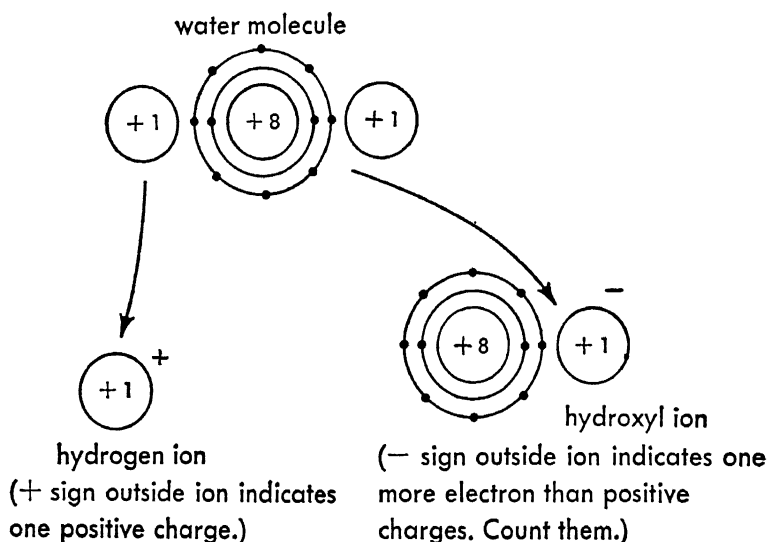


FIG. 3-6

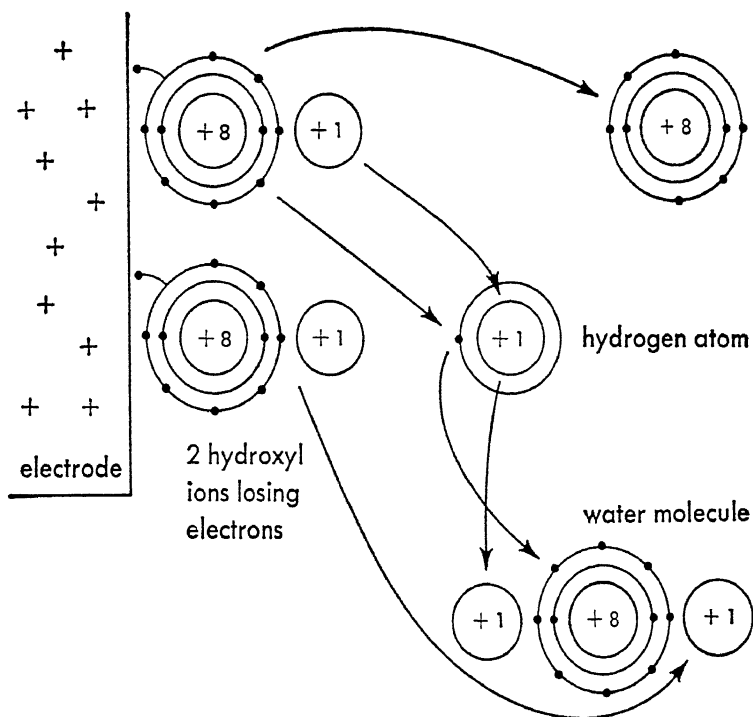


FIG. 3-7

receive from the electric current one electron each, which makes them hydrogen atoms. They combine two by two into hydrogen molecules and bubble up to the surface of the water. At the positive electrode, hydroxyl ions give up their extra electron, and when two hydroxyl ions do this near each other, one oxygen atom snatches a hydrogen atom from the other oxygen, forming a molecule of water and a free oxygen atom, as in Fig. 3-7. The free oxygen atoms combine two by two into molecular oxygen and bubble up from the positive electrode.

Electrons going into one side of the cell are taken up

MAKING ELECTRICITY WORK

by hydrogen ions, and hydroxyl ions give up electrons to the electrode at the other side of the cell. The effect is the same as if an electric current were passing through the cell and completing the circuit to the battery. The battery returns to the atoms the same amount of energy that was released when the oxygen and hydrogen combined into water.

As hydrogen and oxygen are formed, the supply of ions in the water near the electrodes of the cell is depleted. Then the charge provided by the battery to the electrodes attracts more distant hydrogen and hydroxyl ions, hydrogen ions to the negative terminal and hydroxyl ions to the positive terminal, so there is an actual flow of ions through the water.

Action of Lye in Hydrolysis

If the cell contained only water it would be ineffective, because very few molecules of water ionize spontaneously

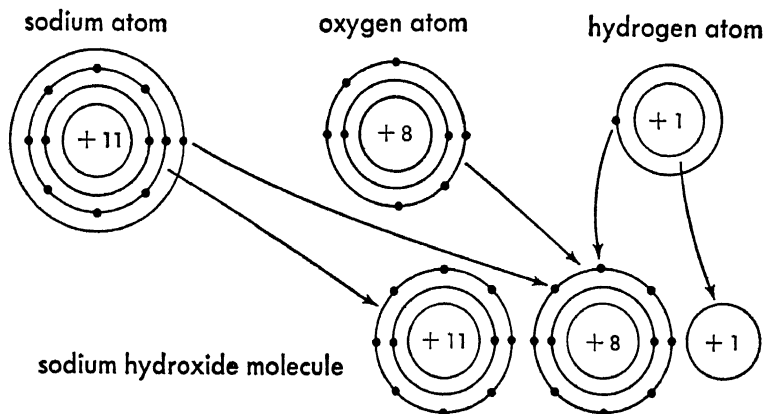


FIG. 3-8

—that is, separate of their own accord into hydrogen and hydroxyl ions. It would take hours to collect a little hydrogen and oxygen. Lye dissolved in the water solves the problem, but to see *how*, you must understand what lye is like chemically.

Lye is sodium hydroxide. Its molecule consists of an oxygen atom, a hydrogen atom, and a sodium atom. The separate atoms and the molecule are shown in Fig. 3-8. Sodium hydroxide is like water but has a hydrogen atom replaced by a sodium atom; it is unlike water in other respects. When dissolved in water, sodium hydroxide ionizes heavily—that is, the water gets into most of the molecules and splits them up into sodium ions (sodium atoms without outer electrons), which are positive, and hydroxyl ions, which are negative, as in Fig. 3-9. Some chemicals don't dissolve at all in water, and those that do ionize to varying degrees. The reason lye will burn you is that it ionizes so readily. All strong alkalies—lye

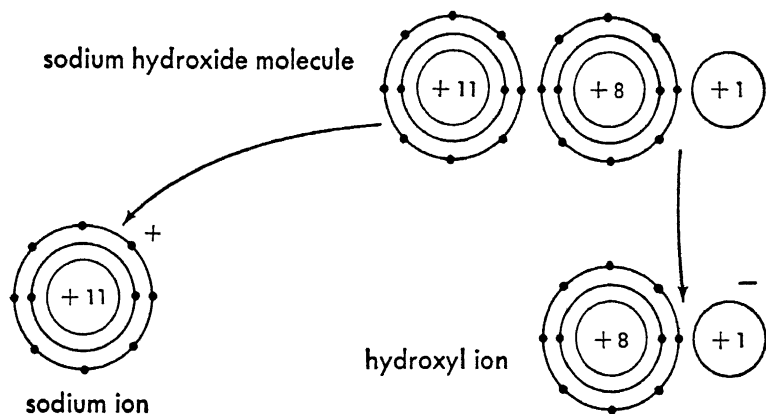


FIG. 3-9

is one—and all strong acids are strong *because* they ionize readily.

Its ready ionization is one reason why lye is used in the hydrolysis of water. So many ions are present that there is never any depletion of ions near the electrodes, and current therefore flows heavily. You might think that with lye in the cell sodium metal would be formed at the negative electrode, because a sodium ion would be able to pick up an electron and become a sodium atom. This actually happens, but as sodium is formed at the negative electrode it immediately reacts with water, displacing a hydrogen atom from a water molecule, as in Fig. 3-10. In doing so the sodium atom provides for the hydrogen atom the electron it just received from the electrode. Hydrogen bubbles up, and the new sodium hydroxide molecule formed ionizes into sodium ions and hydroxyl ions.

At the positive electrode, hydroxyl ions make contact and give up their extra electron, thus forming water and oxygen as before when plain water was broken up by a current. But now there are many more hydroxyl ions from the sodium hydroxide.

You can see that if the hydrogen and oxygen were allowed to bubble up into one container, the result would be a highly explosive mixture of the two gases. All of the energy from the battery which had gone into separating the water into the two gases would be available almost instantly if a spark started them combining. Since the hydrogen is produced at the negative electrode and the

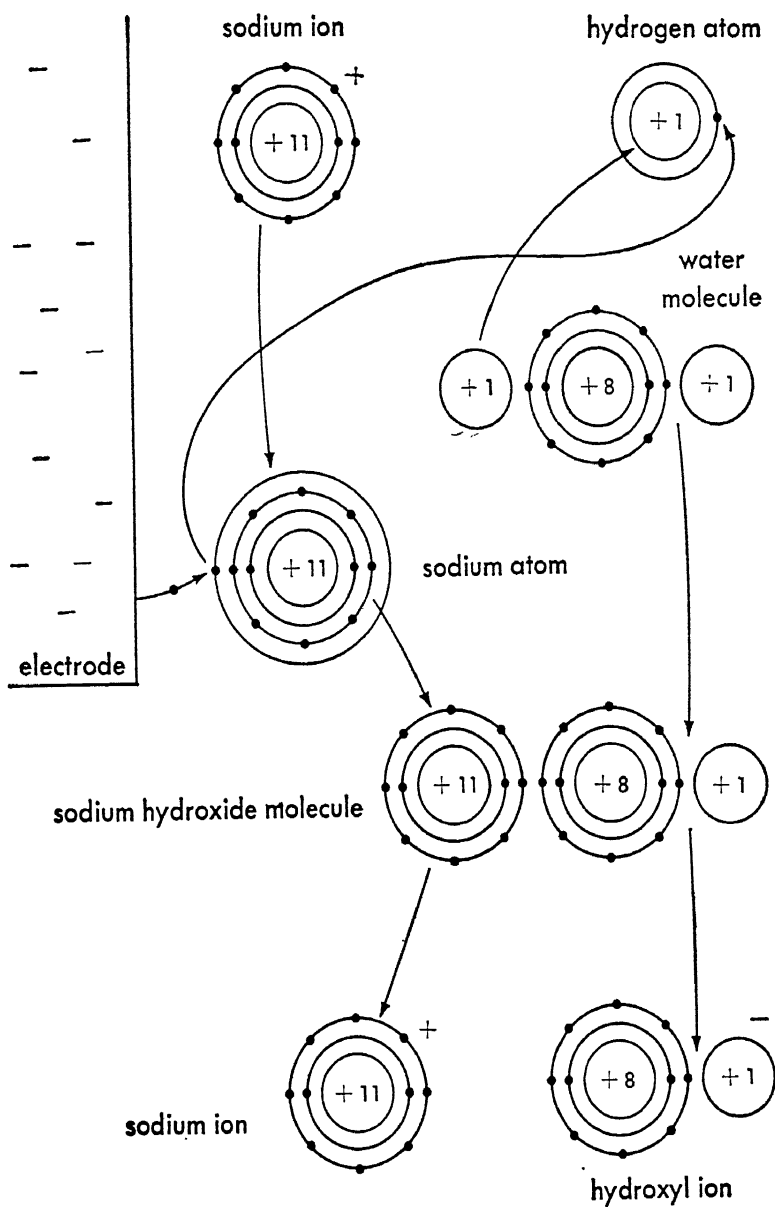


FIG. 3-10

MAKING ELECTRICITY WORK

oxygen at the positive electrode, the two gases can be collected in separate containers as you see it being done back in Fig. 3-5.

The voltage applied to the cell has to be sufficient to overcome the natural tendency of the ions to retain their ionic state and remain in the solution. Each different kind of ion has this tendency to a different degree and requires a different voltage to make it give up or receive electrons. The voltage required also depends on the substance from which the electrodes are made, the smoothness and other qualities of the electrodes, and many other factors. About $2\frac{1}{2}$ volts is a satisfactory working voltage in a hydrogen-oxygen cell.

MAKING A BATTERY

Any battery is a source of free electrons under electrical pressure and a place to absorb the electrons after they have passed through the circuit. The preceding discussion of the hydrolysis of water will make it easier for you to understand the chemistry of the electric battery. It should also bring out an important point: many different forces are at work in an electrolytic cell. The careful selection of materials and conditions of operation of any cell will determine which forces are given play and which are counteracted to produce only the desired results. A great deal of thought, ingenuity, and experience are required in the design of any working cell. A flashlight battery does its job as well as it does because of the ingenuity which has gone into its many years of development. The forces at work inside the battery were not

clearly understood when the first batteries were made. Over the years new materials were added by trial and error and were retained if they improved the battery, even though scientists could not explain the basis for the improvement. Subsequently scientists found out many of the reasons why.

You can build a battery which will work—it will light the bulb of your conductivity tester—and then you can find out why. You probably cannot buy the very specialized materials to make one just like your flashlight battery, but you can make one that works in much the same way from materials that you can easily pick up around the house.

Flashlight batteries are technically called cells because they have two electrodes and a liquid between them, but popular usage has made it correct to call them batteries. A battery is more than one cell connected in series to give more voltage. You will need a battery of two cells in order to produce enough voltage to light the bulb. The electrodes of your cells will be copper and aluminum. The electrolyte will be a mixture of liquid household bleach (sold under such names as Clorox and Rose-X) and baking soda (sodium bicarbonate). The label of the bleach should specify that it contains approximately 5% sodium hypochlorite.

Construction Steps

Start by cutting two strips of household aluminum foil about 4 inches wide and 12 inches long. Fold one end of each piece and crumple the rest of it loosely, as in Fig.

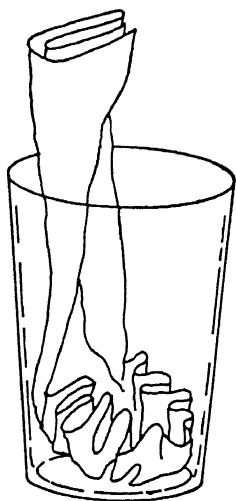


FIG. 3-11

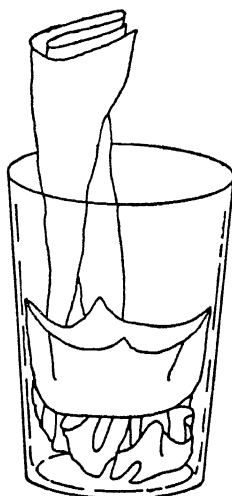


FIG. 3-12

3-11. Then stuff each one into the bottom of a separate 6-ounce jelly glass or tumbler. Cut two double-thick 4-inch squares of paper towel and stuff one of these down on top of the aluminum foil in each cell, as in Fig. 3-12. The paper towel will keep the aluminum electrode from short-circuiting to the copper electrode, which you can now proceed to make.

Cut a piece of lamp cord 2 feet long and strip the two wires apart. Strip 2 inches of insulation from one end of each piece and 12 inches from the other end. Separate the many strands of the 12-inch ends and crumple them into a loose ball about 1 inch in diameter. Place one ball on top of the paper towel in each cell. Join the 2-inch end of one copper electrode to the end of the aluminum electrode of the other cell by twisting them together as in Fig. 3-13.

Remove the flashlight battery from your conductivity

WHERE ELECTRONS COME FROM

tester. Join the wire coming from the base of the bulb to the free aluminum electrode, and slip the end of the free copper wire of your battery under the paper clip that holds the threaded part of the bulb.

The cell is now ready for the electrolyte. Fill each cell with liquid household bleach until the ball of copper wire is nearly covered. After a few moments the filament of the bulb should begin to glow faintly. Now add a level teaspoonful of baking soda right on top of the ball of copper in each cell. The bulb should flash very brightly for a moment and then settle down to burn normally.

In the course of about 15 minutes the bulb will gradually get dim. You can revive it by jiggling the leads to the copper electrodes so as to agitate the electrolyte and bring

Connect wire here from tip of bulb in conductivity tester.

Slip ends of this wire under paper clip that holds threaded part of bulb in conductivity tester.

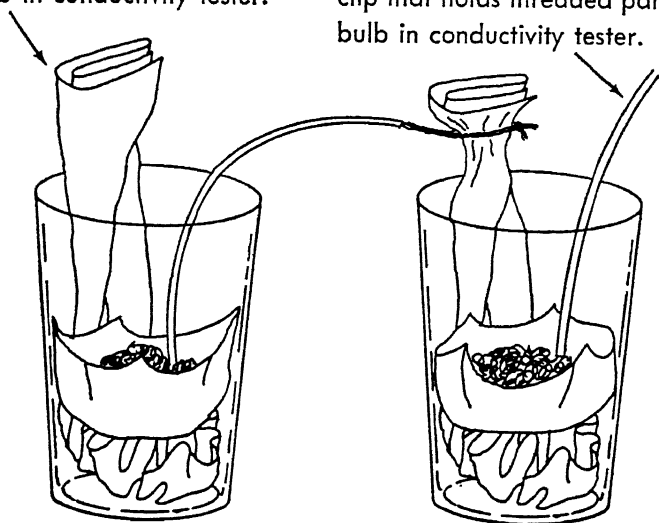


FIG. 3-13

MAKING ELECTRICITY WORK

fresh electrolyte in contact with the copper. You can keep the battery going this way for several hours. Toward the end you can improve the results by adding two tablespoons of bleach and $\frac{1}{2}$ teaspoon of baking soda. The cells finally stop when the aluminum is eaten through and breaks near the surface of the electrolyte.

HOW YOUR HOMEMADE BATTERY WORKS

There are many forces at work inside your cells. Some of them produce the useful current of electrons and some work against it. The forces come from chemical action between the electrodes and the electrolyte. To understand the forces, you have to know what the electrodes and electrolyte are like chemically.

The atoms of aluminum and copper are shown in Fig. 3-14. Aluminum has 13 electrons, with 3, which it can lose easily, in the outermost ring. Copper has 29, with 1 in the outermost ring and 18 in the next ring. It can lose the outer one and one of the 18 easily, but the other 17 only with great difficulty. When a piece of aluminum is placed in water, some aluminum atoms go into solution as ions, each leaving the 3 electrons free in the piece—that is, the



FIG. 3-14

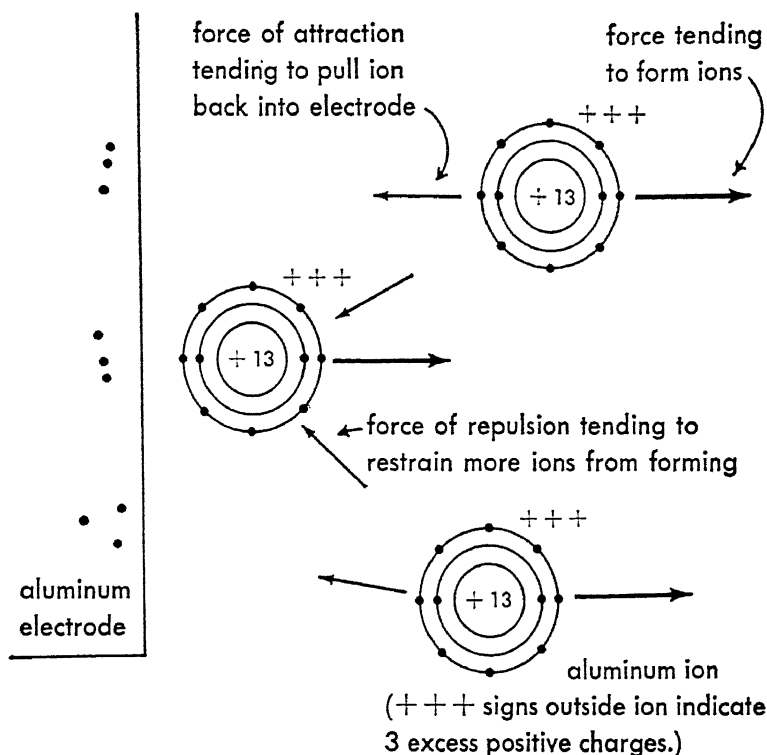


FIG. 3-15

electrode in Fig. 3-15. The ions are positively charged because they have lost electrons, and the electrode becomes negatively charged because it retains the electrons lost by the ions. The force which makes the ions go into solution is one of the main forces that produce the current in your cell. The attraction between aluminum ions formed and the negatively charged electrode is a force which works against the current, tending to pull the ions back into the electrode. As a cloud of aluminum ions forms in the water near the electrode, its positive charge tends to restrain more

MAKING ELECTRICITY WORK

ions—by repulsion of the like charges of the ions—from forming. This is another force working against the current. Many other metals act in the same way as aluminum, each atom leaving one or more electrons free in the piece. Copper leaves two free electrons.

Action of the Chloride Ions

There is another force helping to make the aluminum and copper form ions and give up electrons, but to understand this force you have to understand some chemistry of the electrolyte. Bleach is a water solution of sodium hypochlorite and sodium chloride. The sodium chloride molecule consists of one atom of sodium and one atom of chlorine, as in Fig. 3-16. The sodium has given up one electron to the chlorine and they are then held together by their opposite charges. In solution the water ionizes

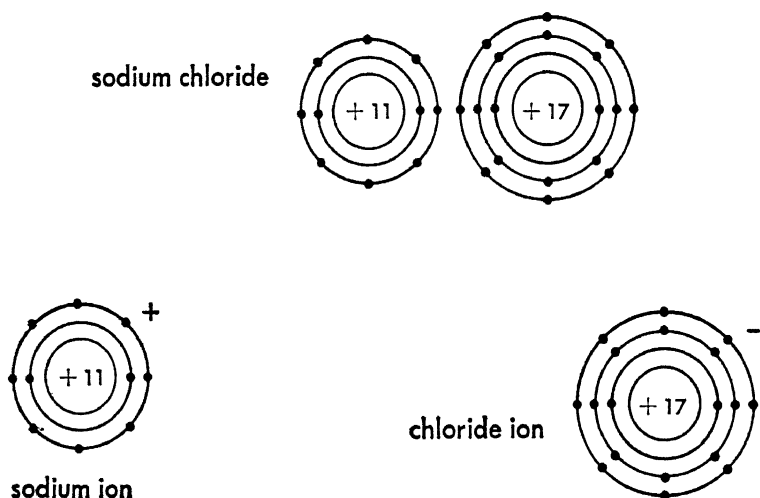


FIG. 3-16

almost all of the molecules of sodium chloride into sodium ions (positive) and chloride ions (negative).

The chloride ions are very corrosive, and they have a way of helping aluminum and copper to ionize and give up electrons to the solid pieces of metal. This corrosive force thus helps to produce current in your cells.

When the copper and aluminum are connected by touching or by an external wire, you might think that, since there are excess electrons in both metals, nothing would happen. But the tendency of aluminum to ionize in water is greater than the tendency of copper to ionize, and in the presence of the corrosive chloride ions the difference is even greater. This means that the force generating free electrons in the aluminum is greater than that in the copper, and electrons are driven from the aluminum to the copper, as in Fig. 3-17, through the external wire.

You remember that one of the forces acting *against* ionization was the attraction of the free electrons in the metal electrode toward the positive ions which have left it and entered into the solution. As electrons leave the aluminum electrode via the external circuit, this attraction is reduced and more aluminum ions can form. As electrons enter the copper electrode this attraction is increased, and some copper ions are drawn back out of solution onto the copper electrode, each ion taking up two electrons as it does so and becoming a copper atom. This process, called "plating out," continues until all the copper ions are back on the copper electrode.

Already you can see how the cell produces a current in one direction, at least up to the time that all the copper

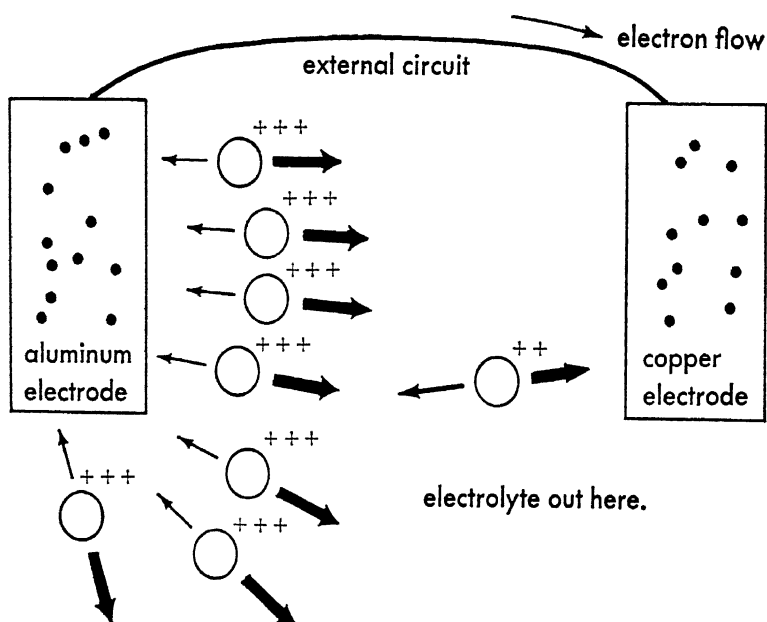
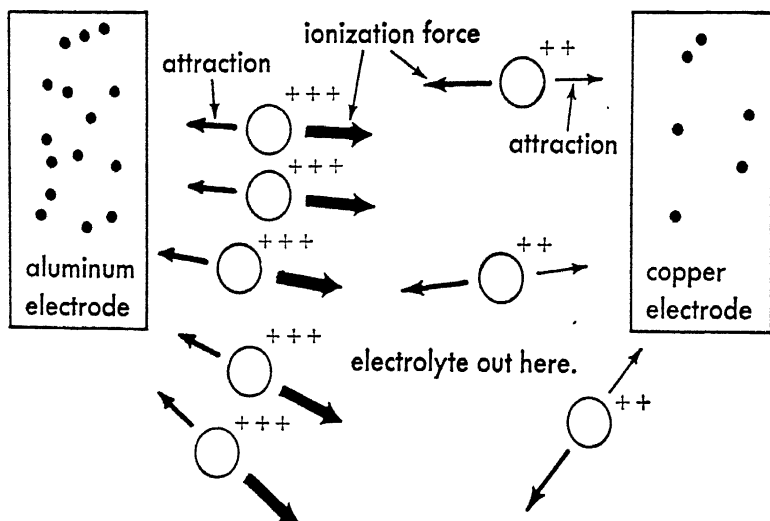


FIG. 3-17

ions are back on the copper electrode. But the current doesn't stop then because of the sodium ions in the electrolyte. Sodium ions are positively charged, and, like copper ions, can plate out on and take electrons from the copper electrode. When they do, they are turned into sodium atoms.

Action of Sodium Compounds

In this way sodium ions help make the cell produce current by taking up electrons to make room for more to come over through the external circuit from the aluminum electrode. But you will remember (Fig. 3-10) that sodium atoms react with water to form sodium hydroxide and hydrogen. The sodium atom holds its electron only long enough to break up a water molecule. During the process it provides the electron necessary to complete a hydrogen atom. This process does two things. It adds a great many hydroxyl ions to the electrolyte, and it produces hydrogen gas.

The hydrogen gas ends up with the electrons, and it should bubble out of the electrolyte and take them away. But some of these bubbles would stick to the surface of the copper and form a layer which would keep the electrolyte away from the copper electrode and stop the process. This is called polarization of the cell. You could keep shaking the electrode to remove some hydrogen, but the coating would re-form as fast as you broke it.

This is where the sodium bicarbonate and the sodium hypochlorite do their work. The sodium hypochlorite molecule consists of one atom of sodium, one atom of

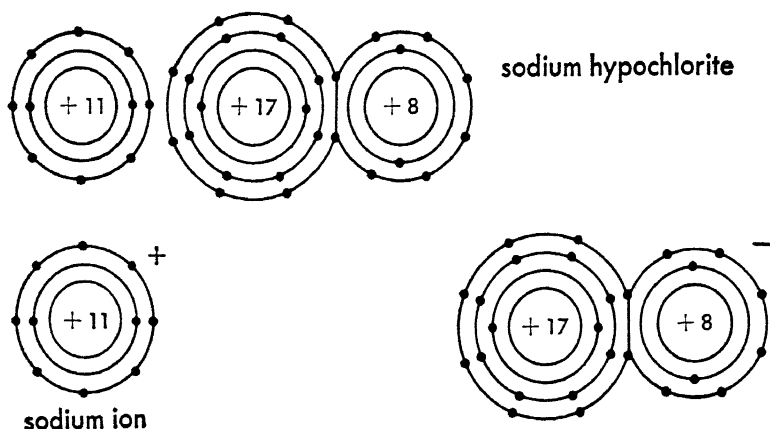


FIG. 3-18

chlorine, and one atom of oxygen combined as in Fig. 3-18. The sodium and chlorine are held together in the same manner as sodium chloride, but the oxygen is held to the chlorine by sharing two of its electrons to complete the oxygen's outermost ring. In water many of the sodium hypochlorite molecules ionize into sodium ions (positive) and hypochlorite ions (negative) composed of chlorine and oxygen. The water does not tend to get between the chlorine and oxygen. Nevertheless the oxygen is easily separated by other forces.

Baking soda is sodium bicarbonate, and its molecule was formed in the manufacturing process out of a hydrogen ion (positive), a sodium ion (positive), and a carbonate ion (negative). A carbonate ion is a carbon atom and three oxygen atoms combined during manufacture with two extra electrons, which give it two negative charges. These are all shown in Fig. 3-19. When bicarbonate of soda is dissolved in water, a good many of the molecules ionize

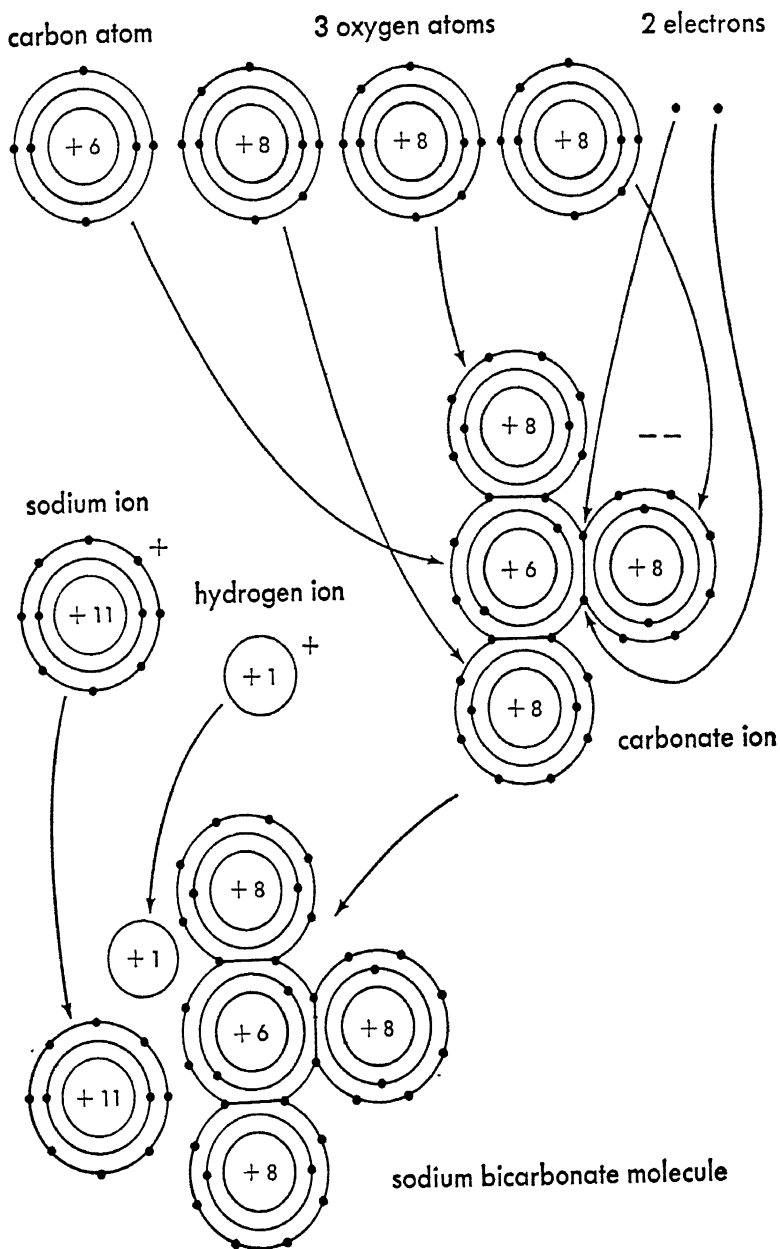


FIG. 3-19

MAKING ELECTRICITY WORK

into sodium ions (positive) and bicarbonate ions in which the hydrogen ions remain attached to the carbonate ions. The bicarbonate ion has one negative charge because it is a combination of a hydrogen ion with one positive charge and a carbonate ion with two negative charges.

The sodium bicarbonate and sodium hypochlorite add plenty of sodium ions to the electrolyte to take up electrons and become sodium atoms, which then break up water into hydrogen gas and hydroxyl ions. But the sodium compounds also add bicarbonate ions and hypochlorite ions. These two ions together remove the atoms of hydrogen and prevent them from forming a coating on the copper electrode. The hypochlorite ions alone would do it by giving up their oxygen to form water with the hydrogen as in Fig. 3-20, leaving chloride ions which help make the aluminum ionize. But, as you saw when you added the sodium bicarbonate, the bicarbonate ion helps the process. You know that sodium bicarbonate neutralizes acids in

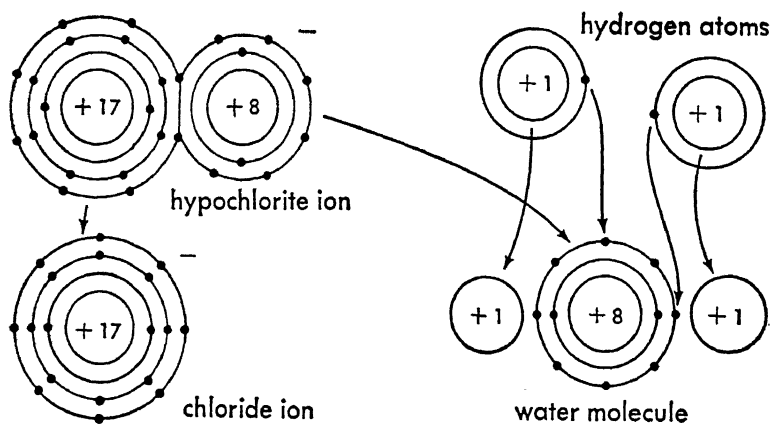


FIG. 3-20

people's stomachs. There is probably some acid formed by secondary reactions in the cell. This acid probably interferes with the transfer of oxygen from the hypochlorite ions to the hydrogen atoms. By neutralizing the acid, the bicarbonate ion would help the cell produce current. When the bicarbonate ion neutralizes an acid, carbon dioxide gas is always formed. Since the gas which bubbles up from your cell is carbon dioxide, the assumption as to how sodium bicarbonate helps the cell is probably true. To demonstrate that sodium bicarbonate does not contribute directly to the current production of the cell, make two fresh cells, using only water and baking soda as the electrolyte. (Don't wash out your old cells and try to re-use them, because you are sure to leave behind some bleach in the washing process.) You will find that these cells are not able to light the bulb. The reasoning in this paragraph should give you an insight into the way theories—right or wrong—are developed from facts which are known.

Excess Aluminum Ions

One more important reaction goes on in the cells. With so many aluminum atoms going into solution as aluminum ions, the electrolyte near the aluminum might easily become so charged with the positive ions that it would exert a force to prevent more from forming, as you will remember from Fig. 3-15. If the cell is to work well, these ions must be removed. They do drift away by diffusion. But you will also remember (Fig. 3-10) that, as the sodium atoms break up water molecules, hydroxyl ions are formed. Hydroxyl ions and aluminum ions together combine to

MAKING ELECTRICITY WORK

form a chemical called aluminum hydroxide. The molecule is shown in Fig. 3-21. This chemical, being insoluble in water, comes out of solution as a jellylike substance. You can see it forming as your cell gets old. This disposes of the excess aluminum ions.

Secondary Reactions

There are many secondary reactions in your cell. The brown coating that forms on the copper wire, some of which stays on the wire and some of which falls to the bottom of the cell, is copper oxide, which gets its oxygen from the hypochlorite ions. The oxide which stays on the wire doesn't seem to interfere with conduction, probably because it is porous. Copper chloride and copper hydroxide are also formed. Copper chloride is blue and colors the

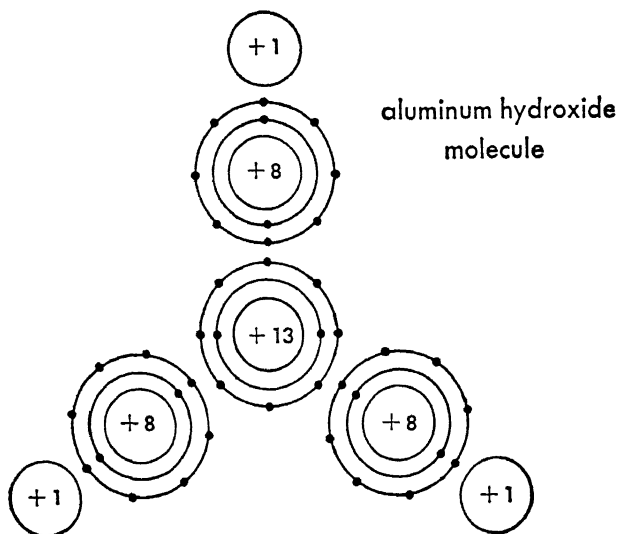


FIG. 3-21

electrolyte when the cells are first started. Copper hydroxide is blue-green and can be seen floating in the surface scum of the jellylike aluminum hydroxide as the cell gets old. Both are floated by entrapped carbon dioxide.

All of these secondary reactions reduce the efficiency of the cell, because as copper atoms leave the wire to form these copper compounds they leave behind electrons.

One secondary reaction, the local action at the aluminum electrode, greatly reduces the life of the cell. It is the same reaction that occurs at the copper electrode. Sodium ions are formed and then break water molecules into hydrogen gas and hydroxyl ions (Fig. 3-10). Then oxygen from the hypochlorite ions forms water with the hydrogen (Fig. 3-20). Finally the hydroxyl ions remove aluminum ions (Fig. 3-21). Each time three water molecules are broken up, one more aluminum ion can go into solution. The aluminum is dissolved much more rapidly than if this reaction did not occur, and it continues whether or not current is being drawn from the cell. Near the surface of the electrolyte the process is speeded up by the presence of oxygen from the air, which acts like and adds to the oxygen from the hypochlorite ions. This is why the aluminum electrode cuts through near the surface of the electrolyte. This action also continues whether or not current is being drawn from the cell. Oil floated on the surface of the electrolyte reduces cutting by keeping air away.

HOW FLASHLIGHT BATTERIES WORK

Except to demonstrate and help you understand battery action and its complexity, your homemade cells cannot

compete with commercial flashlight batteries. But both work in almost exactly the same way. The difference lies in the materials and the methods of manufacture which give commercial flashlight batteries their long life and compact size. Their materials are selected to give these results; the materials of your cell were selected because they are safe and available. Flashlight batteries are sometimes called dry cells, though they might more accurately be called "damp" cells. Like your cells, they have two electrodes and an electrolyte, as shown in Fig. 3-22, but the electrolyte is held in a mixture of solids instead of being in pure liquid form.

Battery Materials

The negative electrode of the flashlight cell is zinc formed into a cylindrical cup so that it serves as a container for the whole cell.

The positive electrode fills almost all the space inside the zinc cup. It consists of a central carbon rod surrounded by a mixture of powdered carbon and a chemical called manganese dioxide. Carbon does not dissolve in water, and manganese dioxide dissolves only slightly. Together the two chemicals form a porous mass around the carbon rod. Carbon can conduct electricity. All through the porous mass the carbon particles touch and form a conducting network so that each manganese dioxide particle is electrically connected to the central carbon rod and its metal cap.

All through the porous mass and in a thin layer between

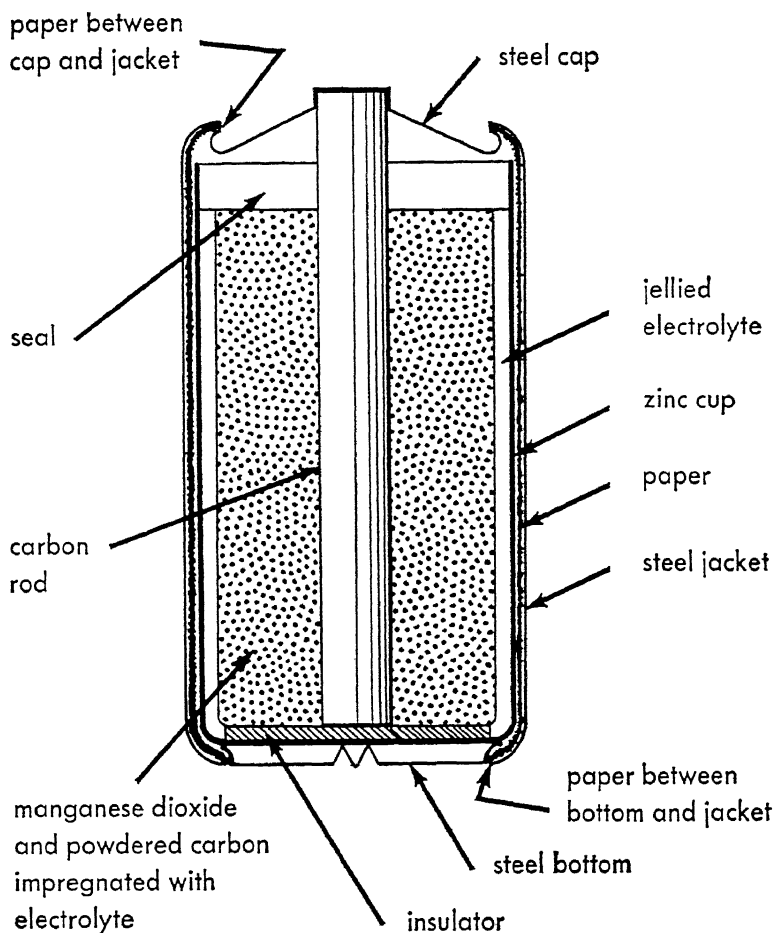


FIG. 3-22

it and the zinc is the electrolyte. The thin layer is jellied and keeps the positive electrode from short-circuiting to the zinc electrode. The electrolyte is a chemical called ammonium chloride with some starch added in the thin layer to make it a jelly. You will see in a moment how the starch is helped to jell.

MAKING ELECTRICITY WORK

The top is sealed with pitch or plastic to make it a "dry" cell.

The reactions that take place are much the same as in your cell:

| REACTION | YOUR CELL | FLASHLIGHT CELL |
|---|--|---|
| Metal atoms in the negative electrode lose electrons and go into solution as positive ions. | Aluminum atoms become aluminum ions. | Zinc atoms become zinc ions. |
| Corrosive ions help ionization of metal at negative electrode. | Chloride ions. | Chloride ions. |
| Positive ions take up electrons from the positive electrode. | Sodium ions become sodium atoms. | Ammonium ions become ammonia gas and hydrogen gas. |
| Product of reaction at positive electrode breaks up water. | Sodium atoms break water into hydrogen gas (supplying electron needed) and hydroxyl ions. Sodium atoms become sodium ions again. | Ammonia gas breaks up water, forming hydroxyl ions and ammonium ions again. |
| Oxygen from ready source removes hydrogen gas by forming water. | Sodium hypochlorite. | Manganese dioxide. |

WHERE ELECTRONS COME FROM

| REACTION | YOUR CELL | FLASHLIGHT CELL |
|--|---|--|
| Chemicals keep electrolyte at correct acidity to aid reactions. | Sodium bicarbonate maintains <i>low</i> acidity, which helps the reactions of <i>this</i> cell. | Ammonium and zinc chlorides maintain <i>high</i> acidity, which helps the reactions of <i>this</i> cell. |
| Metal ions from negative electrode are removed from electrolyte as insoluble compound. | Aluminum hydroxide. | Mostly zinc oxide. |

The differences between your cell and the flashlight cell are in details—but it is the details which make a flashlight cell so much more efficient than yours. Here are a few of them.

The zinc electrode has a little mercury on its surface to help prevent ammonium ions from taking electrons from the zinc, which would waste zinc and keep some ammonium ions from doing their main work at the positive electrode.

The starch in the jellied part of the electrolyte has the happy effect of also helping to prevent ammonium ions from taking electrons from the zinc.

The jelly has some zinc chloride dissolved in it. This provides plenty of zinc ions when the cell is new, so that their concentration won't change during the early life of the cell with accompanying changes in internal resistance. The zinc chloride also helps make the starch gel.

The tiny particles in the porous mass of the positive electrode have together a huge surface area. Electrons stream

in through the carbon to billions of parallel-connected points where they are taken up by the ammonium ions. They don't have to wait their turn to be taken up a few million at a time. This has the effect of producing low internal resistance. A freak cell can drive 4 or 5 amperes through an external circuit of very low resistance.

Gases and Corrosion

One problem with the cell is that very small quantities of hydrogen gas and ammonia gas are given off. If the cell were sealed tightly, these gases would burst the seal. The central carbon rod is made porous so that the gases can leak out through it past the seal. The seal is tight near the zinc so that no air can get to the top of the electrolyte next to the zinc. This prevents accelerated eating away of the zinc caused by the presence of hydrogen atoms and oxygen there together.

You can see that because the zinc acts as a container there needs to be more zinc than will dissolve during the life of the cell. The zinc does not dissolve perfectly evenly, and if it is not thick enough, holes will form and some of the highly corrosive electrolyte will leak out and damage the flashlight. Thickening the zinc would be wasteful and not a positive protection; hence today most cells are covered with a protective steel or plastic jacket, with a layer of paper between the jacket and the zinc. If the zinc is eaten through, the electrolyte is contained. The jacket is partly paid for by a saving in zinc, which can be thinner, and by preventing damage to flashlights. If the jacket is steel, it must be made in two insulated pieces so that it

won't short-circuit the cell. The insulation is slightly porous to allow the gases to escape. (Unfortunately a little water evaporates, too. This is one reason why a cell goes dead in a few years even if it isn't used.) Since the jacket would also be eaten through in time, the zinc still has to be the container. Once the zinc is eaten through, the cell is nearly used up and will probably be disposed of before the jacket is eaten through.

Other Reactions

There are other reactions which take place inside the cell, and some of them interfere with its life. Some of these undesirable reactions occur most readily when heavy currents are drawn. They reduce the voltage of the cell temporarily and increase its internal resistance permanently. For this reason $\frac{1}{4}$ ampere—the current used by a flashlight bulb—is the most that should be drawn from a cell for more than a few minutes. Even at $\frac{1}{4}$ ampere the cell works better when it is used for only a few hours at a time. During the rest periods the zinc ions have a chance to diffuse through the jellied electrolyte. Other undesirable reactions go on even when no current is being drawn, and this is another reason why cells go dead without being used.

A long history of practical experience lies behind the modern flashlight cell. Manufacturers have learned how to select and process their materials carefully to produce long life. Not just any manganese dioxide will do. It must be selected for particle size and crystal structure, or cell life will suffer. Just the right starch must be chosen, and graphite and other forms of powdered carbon must be

mixed in proper proportions or the internal resistance will be too high. Every substance used is subject to this kind of careful selection.

OTHER KINDS OF BATTERIES

A battery is just about the only voltage source you can put in your pocket. The flashlight batteries you have been working with give, as you know, $1\frac{1}{2}$ volts at up to $\frac{1}{4}$ ampere for several hours at a time, and up to 4 amperes for a few moments. They are called D cells. Because D cells won't serve every purpose, however, there are many other kinds for special uses. For big hand lanterns, much more current is required to give the greater light output. They often use No. 6 cells, which are 6 inches tall and $2\frac{1}{2}$ inches in diameter. A No. 6 cell is nothing more than a bigger version of a D cell. It also gives $1\frac{1}{2}$ volts, but it can supply a few amperes for several hours and gives more watt-hours over its useful life. Other sizes and shapes of cells and batteries of cells in series are made for the wide range of flashlights and for other uses. Four No. 6's in series in one steel container is a 6-volt "hot-shot" to run the lights on a small boat. Portable vacuum-tube radios require a low voltage at about $\frac{1}{4}$ ampere and a high voltage at a few hundredths of an ampere. The low-voltage batteries are called A batteries. They can be two or more regular flashlight cells in series or several similar cells in series in one package. The high-voltage batteries, called B batteries, consist of many tiny cells in series in one package. A common B battery voltage is $67\frac{1}{2}$, and the battery contains 45 $1\frac{1}{2}$ -volt cells in series. A and B batteries come

in many sizes and shapes but all consist of $1\frac{1}{2}$ -volt cells in series, enough of them to add up to the required voltage and each big enough to produce the required current.

There are other kinds of batteries which are made with different materials, mercury batteries being the most common of these. A mercury battery gives more watt-hours than a zinc-manganese dioxide battery of the same size. This means that in a hearing aid, for example, a tiny mercury battery will outlast a tiny zinc-manganese dioxide battery. Their disadvantages are that they are heavier and cost more per watt-hour; hence they are used only where small size and long life are very important.

Storage batteries, or wet cells, are another kind of battery. Dry cells, once their internal resistance has risen owing to the deposit of zinc oxide and other chemicals, are useless. But storage batteries can be recharged from a generator many times. When an automobile storage battery is discharged, both electrodes are lead sulfate and the electrolyte is weak sulfuric acid. During charge, the electrical energy is converted to chemical energy. One electrode is converted from lead sulfate to lead and becomes the negative electrode. The other electrode is converted from lead sulfate to lead oxide and becomes the positive electrode. The released sulfate ions make the electrolyte strong sulfuric acid. During discharge the sulfuric acid becomes weak again by reacting with both electrodes, which become lead sulfate again, the lead giving up electrons and the lead oxide taking up electrons. At discharge, the sulfuric acid is weak and at full charge it is strong. Since a weak acid is less dense than a strong acid, the

garage man can test the state of a battery's charge by measuring the density of the acid with a hydrometer.

In an automobile the generator produces more current than is immediately needed when the engine is running fast, barely enough when it is idling and the headlights are off, and of course none when it is stopped. When the engine is running fast the generator supplies the needs of the car and also charges the storage battery. The battery supplies the current that is needed when the engine is idling or stopped.

Another kind of cell, the solar battery, is not a chemical cell but consists of certain carefully prepared materials which convert strong light directly into electrical energy.

But all batteries together provide only a very small proportion of the kilowatt-hours of electrical energy that are used throughout the world. Most electrical energy is produced by generators, and much of it is used up in motors. These will be discussed in Chapter 5, but in order to understand them we shall have to know about magnetism, which is the subject of the next chapter.

CHAPTER 4

THE NATURE OF MAGNETISM

Many of the practical and familiar devices that put electricity to work today would not exist were it not for magnetism. Other means of doing the things now done with magnetism might be found, and indeed many already exist. But motors in their present compact form, the modern system of generating and distributing electric power, countless electrical appliances—and, for that matter, radio and television as they now function—would not be a part of our lives today. Magnetism is not electricity, but it is closely related to it. It is interesting in its own right, and its basic principles will be examined in this chapter.

WHAT ARE MAGNETS?

Like the phenomenon of static electricity, natural magnetism has been known for more than 2500 years. Greek

philosophers in the sixth century B.C. were the first to seek the reason why certain pieces of stone—actually a special type of iron ore—had the ability to attract iron. The Greeks called these stones *magnets* because they were found most plentifully in the Greek province of Magnesia, home of a people called the Magnetes. Some Greek philosophers thought that these chunks of stone had magical properties; others explained their magnetic effect by assuming that the magnets had invisible hooks which attached themselves to invisible rings on the surface of the iron. This didn't explain why some small pieces of iron became magnets themselves when they were brought in contact with a magnet and why others did not. Whatever their explanation of magnetism, the Greeks saw no practical use for it.

It was not until some sixteen centuries later—around A.D. 1000—that the Chinese began using natural magnets, and later magnetized pieces of iron, as compasses for navigation. In the following centuries the magnetic compass opened up the entire globe to explorers, and magnets came to be known as loadstones—stones that pointed the way. In the sixteenth century an English physician, William Gilbert, studied magnets and magnetism in great detail and wrote his classic work *On the Magnet*. It was another three hundred years before the important applications of magnetism to electricity began to be made.

Pure iron, although it is attracted by a magnet, will not become a magnet itself. Iron containing 1 or 2% of carbon combined in it is called steel and will, when magnetized, retain some magnetism. This accounts for the fact that some small pieces of iron—those that contained carbon

—became magnets when brought into contact with a natural magnet and that some pieces, being nearly pure iron, did not. Today special magnet steels made by combining iron with aluminum, nickel, and cobalt are used to make very strong magnets called alnico magnets.

MAGNETIC POLES

You are probably familiar with the fact that magnetism in a magnet usually appears concentrated at its ends, and that the two ends are different. One end of a magnet will attract one end of another magnet and repel the other end. Turn it around and it will repel the first end and attract the second end.

The magnetic ends of a magnet are called its poles. One is called the north pole and the other the south pole. Like poles repel each other and unlike poles attract each other. Magnetic poles might have been arbitrarily designated positive and negative, but it was discovered that a magnet, if suspended so that it can rotate freely in a horizontal plane, will swing around with one pole, always the same one, pointing north. That pole is called the north pole, or (rarely) the north-seeking pole, and the other, which always points south, is called the south pole. This convention for identifying the poles of a magnet was established long before the reason was known why one end always pointed north and the other south when free to do so. The reason is that the earth itself has magnetism, as if there were a huge bar magnet running through the earth with one pole, called the North Magnetic Pole, up north near the geographic North Pole, and the other pole, called the South

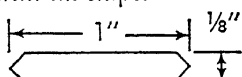
MAKING ELECTRICITY WORK

Magnetic Pole, down south near the geographic South Pole. Since the north pole of a magnet, suspended so it can turn freely, will come to rest pointing toward the North Magnetic Pole of the earth, and since unlike poles attract each other, you can see that according to the convention for identifying the poles of a magnet the North Magnetic Pole of the earth is *magnetically* a south pole.

MAKING A COMPASS

The first practical application of magnetism was the compass. Although the early compasses were not very

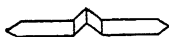
Cut a piece of coffee can with tin snips.



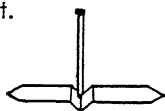
Bend in the center like this . . .



. . . and then like this.



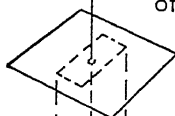
Hit it lightly with a hammer and nail to make tiny dent for the pivot.
Put a tiny drop of oil in the dent.



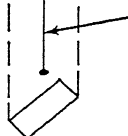
Balance pointer on point of pin.



Cut a 2" square of cardboard.



pin.



Cover head with a piece of Scotch Tape.



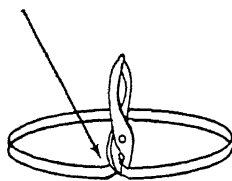
If pointer tilts down, snip from low end until it balances.

FIG. 4-1

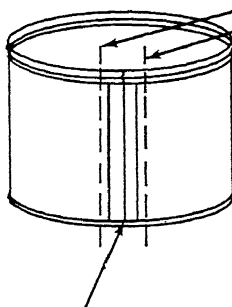
accurate, they made a great improvement in the art of navigation. Before the compass was invented navigators reckoned their direction from the sun by day and the stars by night. When the weather was overcast, as it often is for days at a time at sea, they had no means of telling which way they were headed.

You can make a compass by following Fig. 4-1. Fig. 4-2 shows how to cut up a coffee can to get sheet steel for the pointer and for later projects. With a good pair of tin snips, this is not difficult, but be careful of the sharp edges. After you have constructed the parts, you will have to magnetize

2. Grab inner rim with pliers, twist, and lift out.



3. Cut along here with tin snips, and flatten.



1. Cut out bottom with rotary can opener.

soldered joint of can

4. When flat, cut off top and bottom rims with tin snips.

FIG. 4-2

the pointer with your alnico magnet. At the same time you will be able to identify the poles of your magnet. Mark one end of your magnet and one end of the pointer of the compass. Hold the two marked ends together with the pointer and the magnet at right angles as in Fig. 4-3. Draw the magnet down the length of the pointer, separate the two, and return the marked end of the magnet to the marked end of the pointer. Repeat the stroking operation several times, always in the same direction. Then balance the pointer on the pin. The pointer will line up in a nearly north-south direction. If you don't already know which end points north and which south, you can refer to a map or simply realize that when you face east, where the sun rises, north is on your left. If the marked end of your compass points north, the marked end of your magnet is a north pole.

HOW A MAGNET GETS MAGNETISM

The reason that the pointer became magnetized as it did is as follows. Any piece of iron or steel is made up of billions of natural magnets which need no magnetizing. In an unmagnetized piece of iron or steel, these magnets, which are almost atomic in size, are arranged with their north and south poles in a random fashion. As a result, each magnetic particle has its magnetism neutralized or cancelled by one or more other elemental magnets. If they were free to move, they would arrange themselves north pole to south pole throughout the piece of substance; but, since they are individually very weak magnets, they are restrained from moving by the rigid structure of the solid

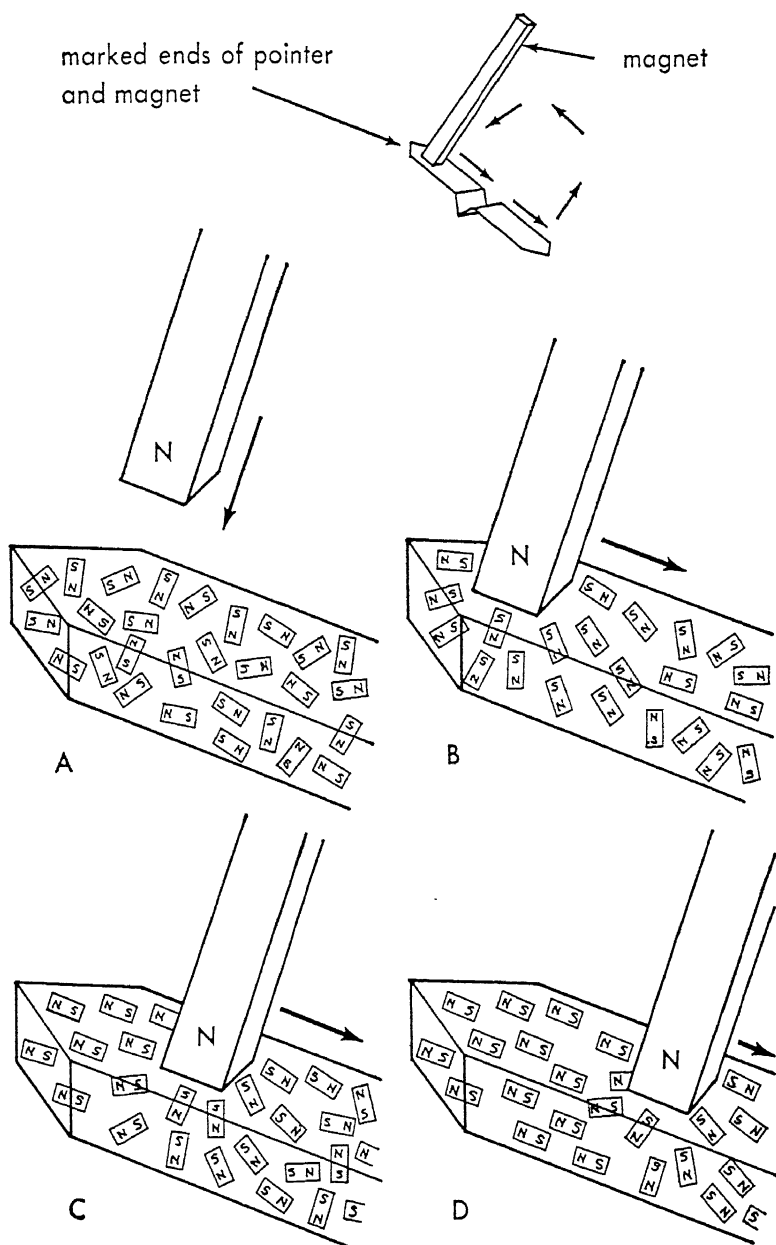


FIG. 4-3

piece. As you placed a pole of your magnet—say the north pole—at the marked end of the steel compass pointer, as in Fig. 4-3, the south poles of many of the magnetic particles in the steel were pulled around to point toward your magnet by its very strong magnetism. As you moved your magnet down the length of the pointer away from the magnetic particles in the tip of the marked end, they began to rotate so that their south poles continued to point toward the north pole of your magnet. As you stroked on down the pointer, this left many of the magnetic particles with their south poles pointing away from the marked end.

It is the nature of steel, owing to the arrangement of the carbon atoms among the iron atoms, that when the magnetic particles are rearranged by a strong magnetic force some of them remain rearranged. In pieces of iron that contain very little carbon, the magnetic particles are arranged in a structure which, although it permits them to become rearranged under the influence of magnetic force, causes them to spring back into place when the force is removed. In steel only some of them spring back. For this reason, pure iron cannot be used to make permanent magnets.

The first time you stroked the pointer you permanently rearranged some of the magnetic particles, and each successive time you permanently rearranged some more. You might have simply touched the south pole of your magnet to the end of the pointer that you wanted to make the north pole of the compass. Some of the magnetic particles in the pointer would become permanently rearranged, because magnetism is carried easily through iron and steel,

but the pointer would not have been quite so strongly magnetized by that method.

Testing the Theory

A simple experiment can demonstrate the fact that a magnet is made up of many magnets end to end. Straighten a paper clip and magnetize it with one end of your alnico magnet. Cut the magnetized paper clip in two at about the center. You will find that the ends of the two halves on either side of the cut will attract each other and repel the opposite end of the other piece. Cut one of the halves in two again, and its halves will act in the same way but less strongly.

Magnetism and Heat

Since the rigid structure of an unmagnetized piece of steel prevents the magnetic particles from lining themselves up, you may wonder why molten steel does not become a strong magnet and why it does not remain magnetized when it is cooled. The reason is that when steel is heated to very high temperatures but still well below its melting point, its atoms are so agitated that the steel will lose any magnetism it may have had.

You can demonstrate this fact. With the tip of a pair of pliers, grip your compass pointer at a point near its pivot and hold the pointer over a gas flame until it is red hot. Dip it in water, wipe it clean, and relubricate the pivot. When you place the pointer back on the pin, you will find that when you spin the pointer it will stop at any random position and is no longer a compass. Remagnetize the

pointer with your magnet and it will once again be a compass.

TRUE NORTH AND MAGNETIC NORTH

Magnetic compasses do not point exactly toward the geographic North and South poles of the earth. One reason is that the magnetic poles of the earth are not located at the geographic poles, which are the ends of the axis on which the earth rotates. The North Magnetic Pole is located in northern Canada, and wanders between about 70 and 76 degrees north latitude and 95 and 102 degrees west longitude. If you look it up on a large-scale map of the world, you can see where it is in relation to the geographic North Pole. Compasses in Fort Wayne, Indiana, pointing at the North Magnetic Pole also point true north. In New York compasses point to the North Magnetic Pole, but there they point about 11 degrees to the west of true north, and in San Francisco they point about 18 degrees east of true north. This difference between true north and magnetic north is called the *declination* of magnetic north, *east declination* when the compass points east of true north, *west declination* when it points west.

The magnetic declination is known accurately for most places on the earth's surface and is often recorded on maps. It is determined by comparing the reading of an accurate compass with the direction of true north as indicated by sightings on certain stars. Because the locations of the magnetic poles are gradually shifting, the declination changes slowly over the years. The declination cannot be

determined solely by geometry and the known location of the magnetic poles, because local disturbances in the earth's magnetic field contribute to the declination at many places.

A compass is deflected by other things besides the earth's magnetic field. Iron and steel in the hull of a ship, for instance, necessitate corrections in the reading of a compass. And a steel wrench in your pocket can produce a false reading. You can see how this works. Hold an unmagnetized piece of steel—the lid of a coffee can for instance—near each tip of your compass pointer. Each will be attracted to the steel in turn.

A magnet will also deflect the compass pointer, but, unlike unmagnetized iron and steel, each pole of a magnet will attract the unlike pole of the compass pointer and repel the like pole. In this way you can identify the poles of any magnet you make or obtain. A piece of steel is unmagnetized if several spots on it will attract either end of the compass pointer. If it were magnetized, one of the spots chosen would be sure to attract one end of the pointer and repel the other.

Straighten a paper clip and magnetize it as you did your compass pointer. Identify the poles of the magnetized paper clip. Now bend the clip double into the shape of a hairpin. Hold the bend near each end of the compass pointer with the two ends of the clip held away from the compass. You will find that some spot on the bend will attract either end of the compass pointer. The north poles of the elemental magnets in the clip that face the pointer on one side of the neutral spot just balance the south poles

that face the pointer on the other side of the neutral spot. This explains why you can't test only one spot on a piece of steel to see whether it is a magnet.

Poles Can Be Anywhere

The poles of a magnet are not always at its ends. An unusual arrangement of poles can be produced. Straighten a paper clip and check with your compass to make sure that it is unmagnetized. Bring the south pole of your alnico magnet straight down onto the center of the straightened clip and remove by lifting it straight up, without sliding it along the clip. You will discover that both ends of the clip are south poles! The north pole is, of course, somewhere on the clip. Find it with your compass.

The earth, which doesn't have any ends except poetically, has magnetic poles.

THE MAGNETIC FIELD

In your compass you have seen the force of a magnet exerted at a distance without the magnet's having to touch the object—a piece of iron or another magnet—on which it is exerting the force. In much the same way the earth exerts its force of gravity on an object that is not touching the earth—an airplane, for example. The force of gravity is exerted radially out from the center of the earth, as in Fig. 4-4. There is only one kind of gravity, a force of attraction. Magnetic poles, however, always occur in pairs; one end of each natural magnetic particle is a north pole and the other is a south pole. The force of attraction between them is distributed as in Fig. 4-5. This pattern of

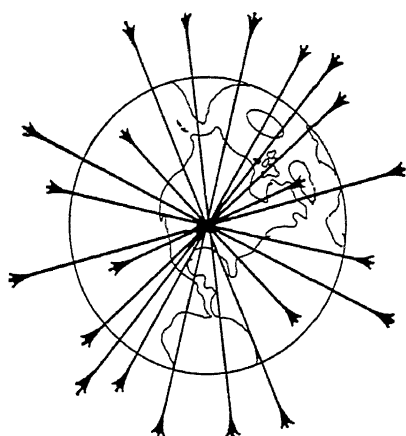


FIG. 4-4

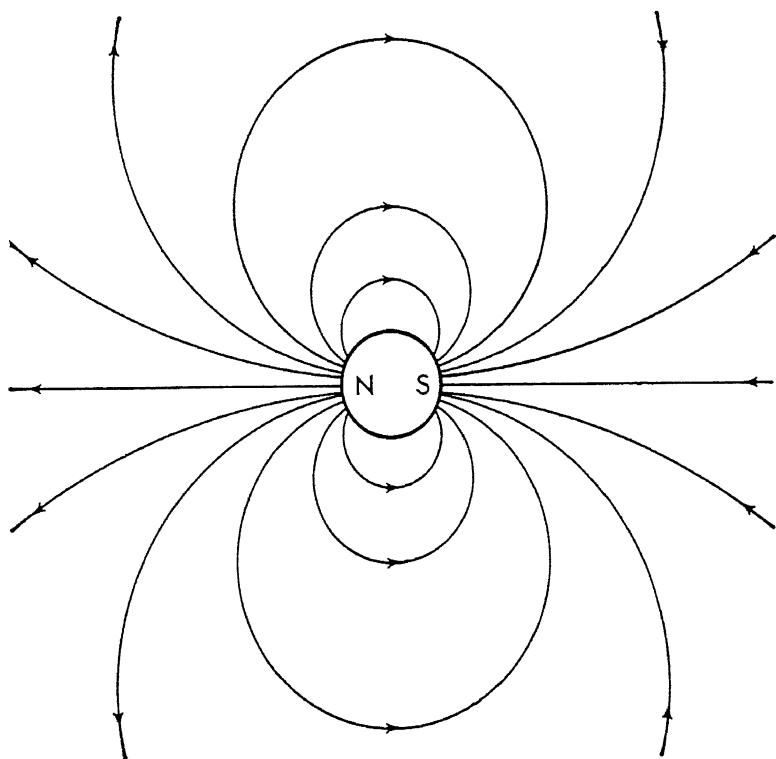


FIG. 4-5

MAKING ELECTRICITY WORK

force is called the *magnetic field* of the magnetic particle. Where the field is strongest, the lines in Fig. 4-5 are closest together. When opposite poles of two magnetic particles are near each other, the distribution of their fields changes to that in Fig. 4-6. Notice that the total field is stronger, as indicated by the density of the lines, and also that the

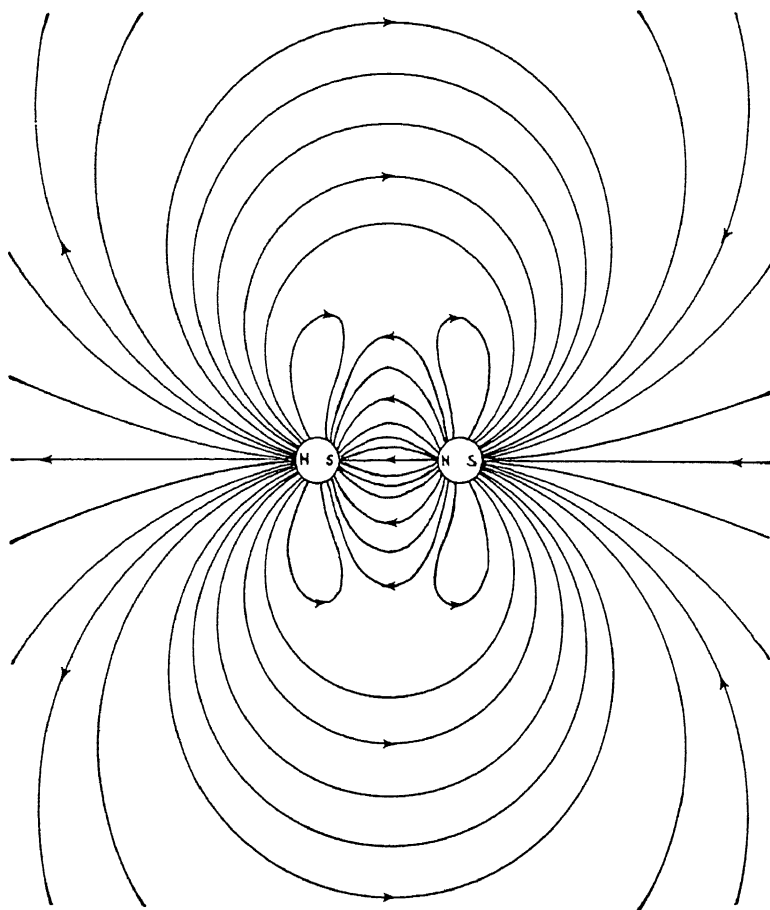


FIG. 4-6

pattern of the lines *beyond* the magnetic particles is much the same shape as for a single magnetic particle.

Since a magnet is composed of billions of magnetic particles arranged end to end, it follows that the field outside it, as in Fig. 4-7, is very similar to the pattern in Fig. 4-6. The field in Fig. 4-7 is much stronger than that in

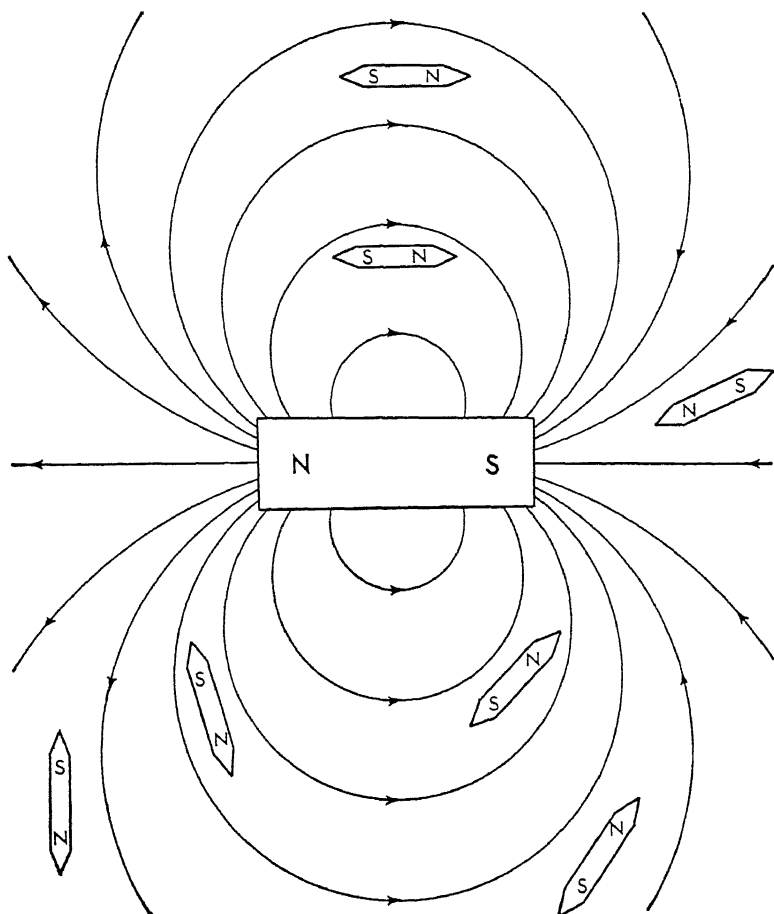


FIG. 4-7

MAKING ELECTRICITY WORK

Fig. 4-6, but if the same scale of line density were used, Fig. 4-7 would have to be solid black. Fig. 4-7 also shows how the force of the field around a magnet would act on a compass placed at various points in the field. You can test this pattern with your magnet and compass. The arrows in Figs. 4-5 to 4-8 show the direction along each

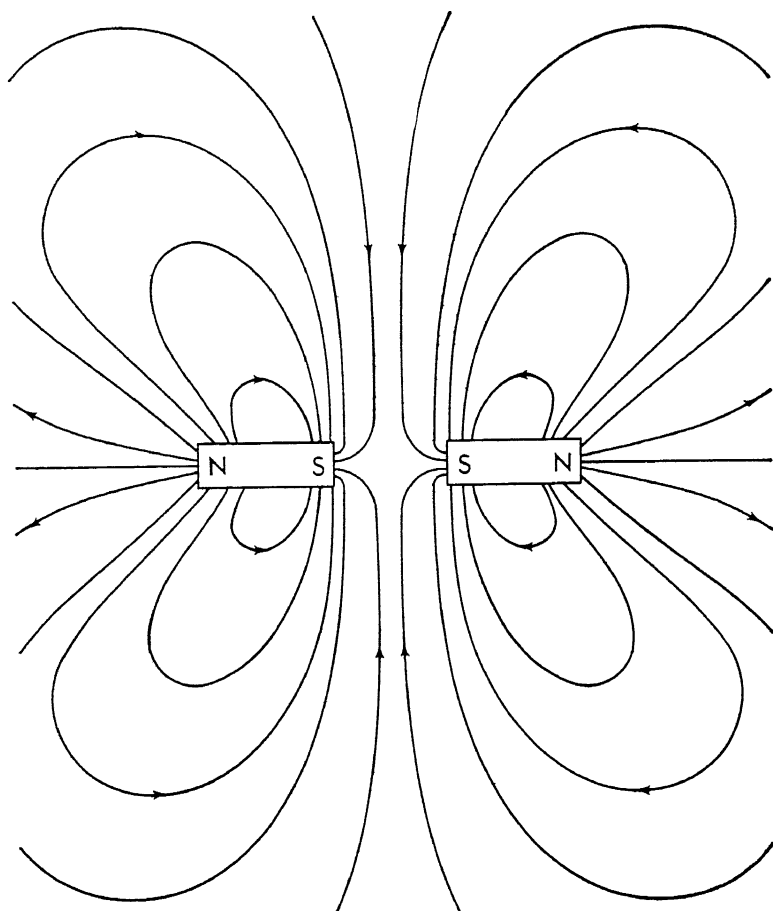


FIG. 4-8

line in which the north pole of a compass would point if it were placed on the line.

When like poles of two magnets are brought end to end, the distribution pattern is rearranged as you see it in Fig. 4-8.

SOME PROJECTS INVOLVING MAGNETS

Here are some things you can do with strong magnets to entertain a younger brother or sister and their friends, or to please your mother.

Magnetic Puppet Show

Make a pasteboard stage and some paper puppets like the ones in Figs. 4-9 and 4-10 and decorate them. When you hold an alnico magnet against the back of the stage it will be able to hold one of the puppets against the front of the

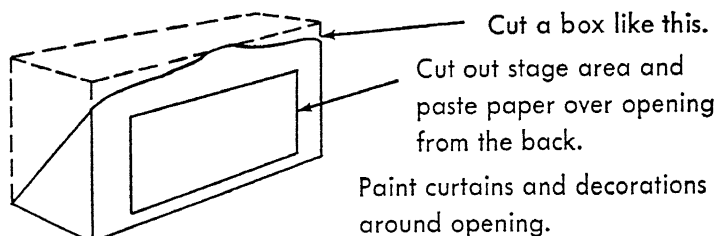


FIG. 4-9

Cut out paper figures.
Decorate front. Scotch
Tape paper clip to back
of head.



FIG. 4-10

MAKING ELECTRICITY WORK

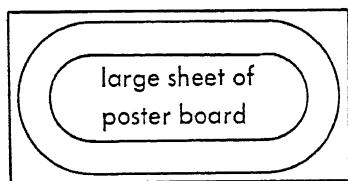
stage by magnetic attraction for the paper clip at the puppet's head. You can then move the magnet around, and the puppet will move with it to act out a play.

Horse Race

The same principle can be applied to a horse-race game. Make a race track and horses like the ones in Figs. 4-11 and 4-12. Each player holds his magnet under the track at the starting gate and puts his horse on top. At the starting signal each tries to drag his horse around the track to the finish line first.

Magnetic Pot Holders and Notice Board

You can sew a tiny magnet into a pot holder and it will stick to a convenient spot on the side of the stove. But

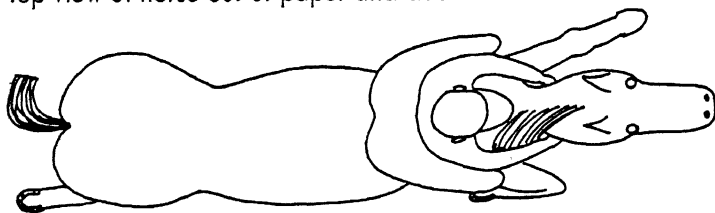


Draw oval track,

Decorate inside and outside of track with top views of people, grandstand, trees, etc.

FIG. 4-11

Cut top view of horse out of paper and decorate.



Hold paper clip under head with Scotch Tape.

FIG. 4-12

perhaps this is where you got your magnet in the first place! A magnet will hold a shopping list or other paper to the door of a steel kitchen cabinet.

ELECTROMAGNETISM

An electric current flowing in a wire will deflect a nearby compass. This means that a current produces a magnetic field. You can see this by holding a wire *above* your compass pointer, near and parallel to it, and then running a current through the wire as in Fig. 4-13. It doesn't matter if the wire is insulated; but, if it is, scrape it bare where you connect it to the battery. Magnetism goes right through insulation. The size of the wire is unimportant. A short piece of any of the wire you have used will have *almost* no resistance compared to the internal resistance of the battery. It is the internal resistance of the battery which will determine how much current flows—about 4 amps, you will remember, for a new cell. Keep the circuit closed for only a moment, because the battery will be used up very rapidly. Before you start, the compass will be pointing north and the wire will be running north-south. With the electrons flowing south in the wire, the north end of the pointer will swing around to point west. A magnetic field is created around the wire just as if the current produced a magnet around the wire, with the magnet's poles placed on either side of the compass pointer as in Fig. 4-14.

If the wire in Fig. 4-13 is placed *under* the compass pointer, the north end of the pointer will swing east as in

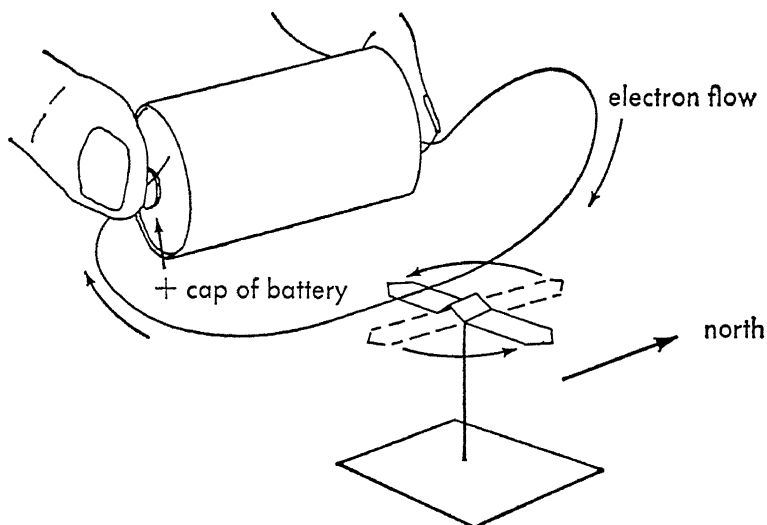


FIG. 4-13

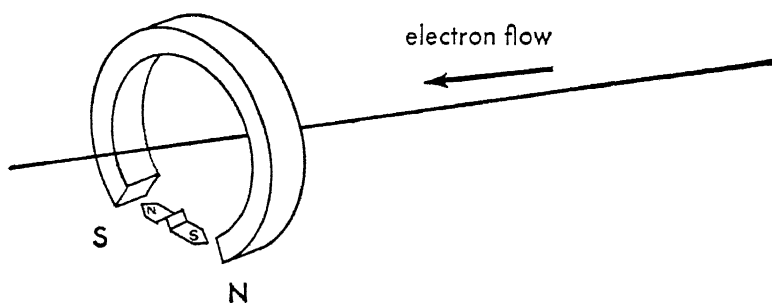


FIG. 4-14

Fig. 4-15. A magnetic field is produced just as if a magnet had been created with its poles located on either side of the compass pointer as in Fig. 4-16. This is really another way of saying that with electrons flowing in a wire a circular magnetic field is produced around the wire. If we employ the convention that was used in Figs. 4-4 to 4-8 for drawing magnetic fields, the arrows on the circular

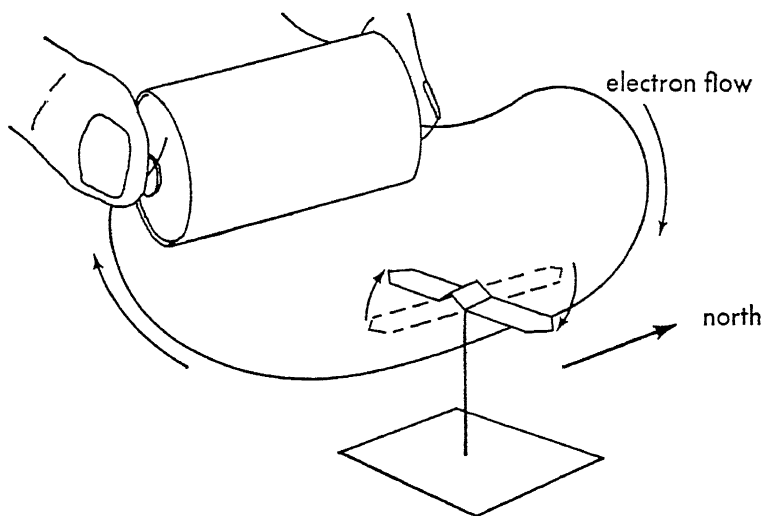


FIG. 4-15

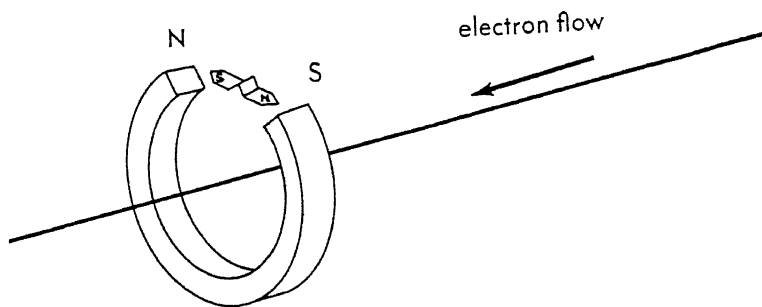


FIG. 4-16

field would point in a clockwise direction if the electrons in the wire flow toward you.

The Left-hand Rule

You can remember the position of the poles of the imaginary magnet created around the wire by using what is called the left-hand rule. If you point the thumb of your

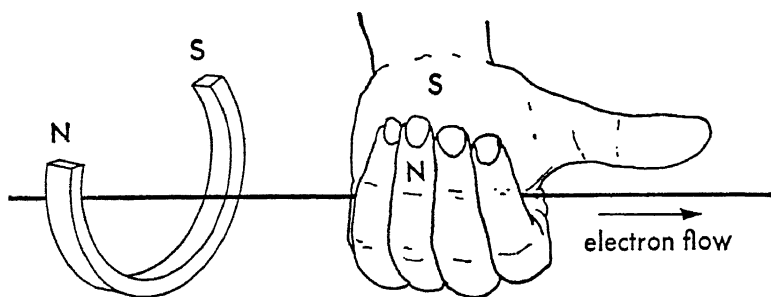


FIG. 4-17

left hand along the wire in the direction of electron flow, the tips of your fingers will represent the north pole and the heel of your hand the south pole of the magnet created. This is illustrated in Fig. 4-17.

Turns of Wire Carrying Current

The magnetic field created around a wire carrying a current is not very strong even when a heavy current, such as 4 amperes, is flowing. Since there are weak imaginary magnets created all along the length of the wire, the

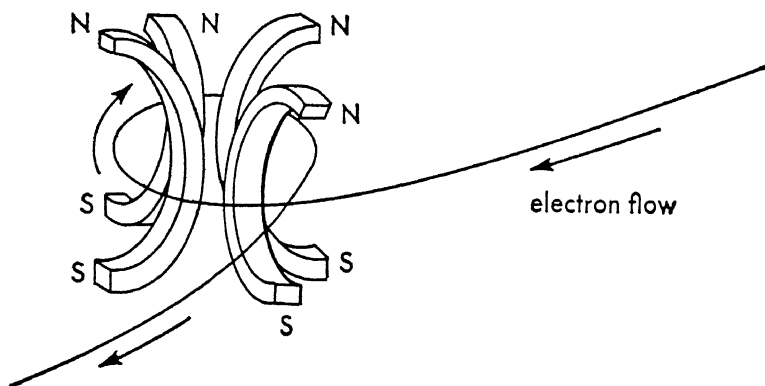


FIG. 4-18

magnetic field can be concentrated in one place to make a stronger magnet by looping the wire into a turn as in Fig. 4-18. Then the magnets formed around each small section of the turn combine to form a single stronger magnet. Check Fig. 4-18 against the left-hand rule to see that the magnets have been drawn correctly.

The Left-hand Rule for Turns

The left-hand rule still applies to finding the poles of the magnet formed by a turn of wire, but there is another

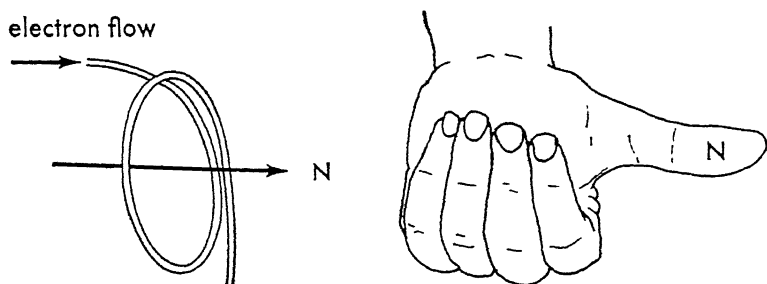


FIG. 4-19

version of the rule which is easier to use. With the fingers of your left hand pointed around the turn in the direction of electron flow, the tip of your thumb represents the north pole of the magnet created. This is illustrated in Fig. 4-19. Check this new version of the left-hand rule against Fig. 4-18.

The Size of the Turn

The strength of the magnetic field formed by a turn of wire carrying a given current is the same regardless of

the size of the turn. Since there are more inches of wire in a larger turn than in a smaller turn, and since each inch of wire produces the same amount of magnetism, there is more magnetism produced in the larger turn, but the magnetism produced is more spread out. You can see this idea better if you imagine a lot of one-pound weights spread out on a floor. Suppose you have 100 of them spread out evenly on a 10-foot-square floor and another 25 of them spread out evenly on a 5-foot-square floor. In each case you would have a load on the floor of 1 pound per square foot, even though you had four times as much weight on the 10-foot-square floor as on the 5-foot-square floor. In this example the total weight is like the *amount* of magnetism, and the weight per square foot is like the *strength* of the magnetic field.

Reluctance

The magnetic field produced by a turn of wire carrying current is generated in air without any iron's being present. If iron is placed inside the turn, however, the magnetic field becomes much stronger, for reasons that will become clear in a moment. The magnetic field around a turn of wire is not moving, but there is a parallel between it and a current flowing in a circuit. It is almost as if the magnetic force around the turn were a voltage and the air in which it exists were a conducting path of high resistance. When a piece of iron is placed inside the turn, it is as if part of the highly magnetic-resistant air were replaced with a good conductor of *magnetism*. If a poor conductor is replaced by a good conductor in an electric circuit, more current

THE NATURE OF MAGNETISM

flows. In a magnetic circuit more magnetism is produced. The more of the air path that is replaced by iron, the more magnetism is produced. Fig. 4-20 shows five progressively better magnetic circuits around a turn. The equivalent of resistance in an electric circuit is called *reluctance* in a

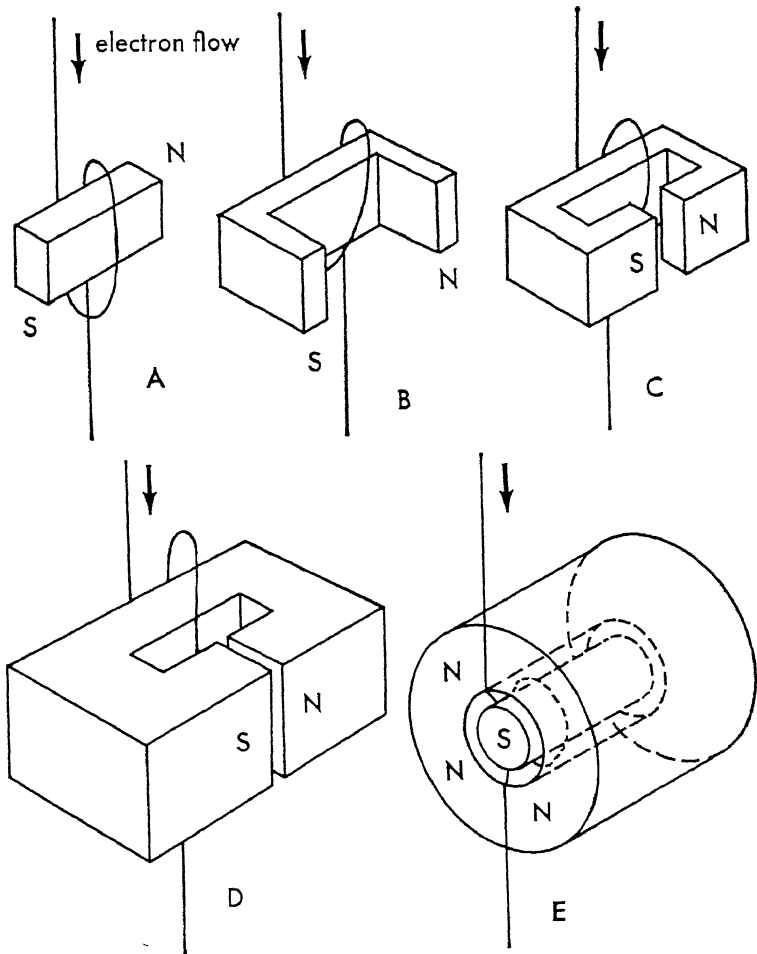


FIG. 4-20

magnetic circuit. In Fig. 4-20, *A* shows a high-reluctance magnetic circuit, and *E*, a low-reluctance magnetic circuit.

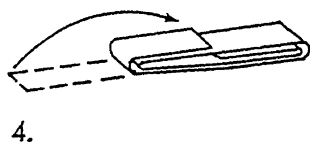
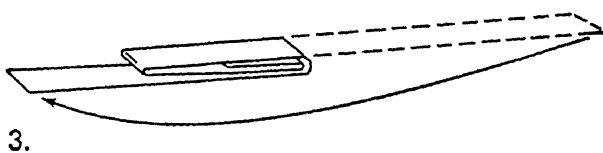
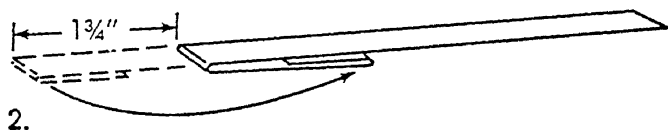
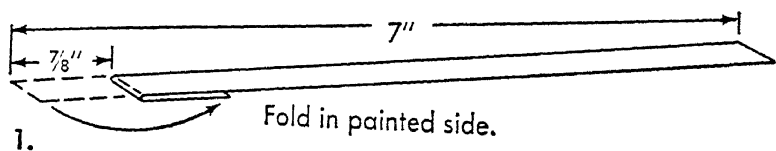
Ampere-turns

Still more magnetic force is produced if more turns of wire are added to form a coil. Then, as the current flows around each turn of the coil, the magnetism produced is added to the magnetism produced in the other turns. The equivalent of voltage in an electric circuit is called *ampere-turns*, which is the unit of magnetic force, in a magnetic circuit. Ampere-turns is the number of amperes flowing multiplied by the number of turns through which they flow.

The more ampere-turns applied to a given magnetic circuit, the more magnetism produced. Also, the more iron and the less air in a magnetic circuit, the more magnetism produced.

BUILDING AN ELECTROMAGNET

You can build an electromagnet with a core similar to the one in Fig. 4-20*B*. Make the core from a strip of coffee can $\frac{1}{2}$ inch wide and 7 inches long. Although coffee-can steel does retain some permanent magnetism, the strength of your electromagnet when current is flowing in the coil will be much greater than when the current is turned off. Bend the strip as in Fig. 4-21, using a pair of pliers to start the bends straight along the bend lines. Then fold the bend the rest of the way by hand, being careful of the sharp edges. Finally squeeze the bends tight with the pliers. The last two bends are made all the way with the pliers.



4A. Same as 4 but showing actual appearance after all bends are squeezed flat.

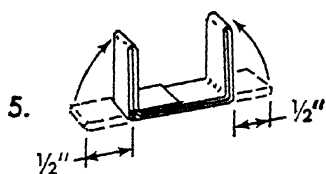


FIG. 4-21

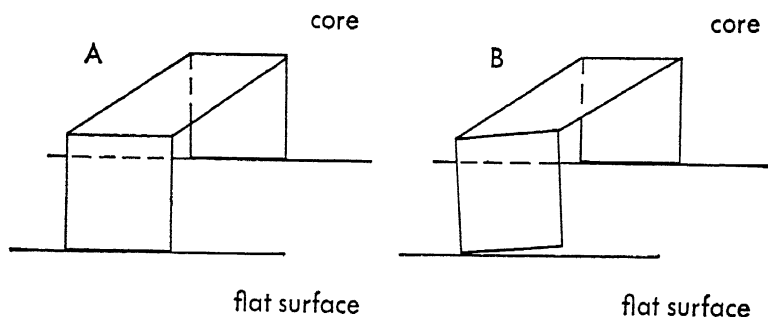


FIG. 4-22

Place the core with its tips touching a flat surface, and see that both tips rest flat all along their edges as in Fig. 4-22A. If they do not, as in Fig. 4-22B, twist the core until they do.

Wrap the core with Scotch Tape as in Fig. 4-23 so that none of its edges will cut into the enamel on the magnet wire when you wind the coil. Leave the tips of the core bare so that when the core is a magnet, the tips will make good magnetic contact with the iron it is going to attract.

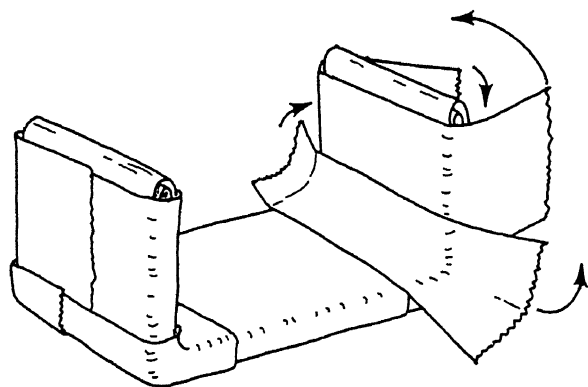


FIG. 4-23

Measure off 50 feet of magnet wire. Magnet wire kinks easily because it is very thin; hence you will have to handle it carefully. The best way is to measure with a tape measure how long a piece will go once around the back of a chair. Suppose you measure 30 inches. Since there are 600 inches in 50 feet, 20 turns (600 divided by 30) around the back of the chair will be 50 feet. Attach one end of your magnet wire to the back of the chair first, and then wind the wire around it. As you wind your magnet, *unwind* the wire a turn at a time from the chair. (If you *pull* the wire from either the coil or the chair back, you will kink it.) Start with 2 feet of wire free for making the connection to the batteries, and wind as in Fig. 4-24 until 2 feet of wire is left. Count

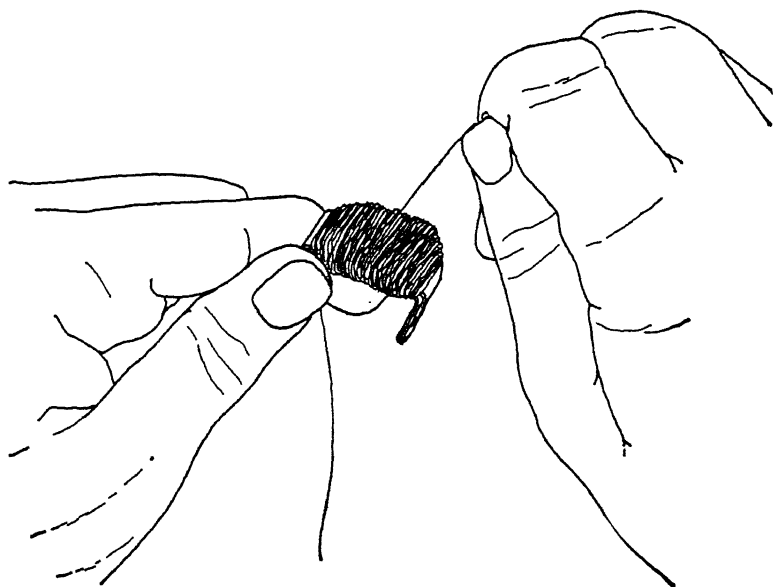


FIG. 4-24

MAKING ELECTRICITY WORK

the number of turns you make. (Turns are easier to count if you use counters—pennies or paper clips—to keep track of the hundreds. Otherwise it is easy to miscount by a whole hundred.) You should get about 400. Then wrap tape around the coil to keep it from coming undone. Clean both ends of the wire as you did in Chapter 1.

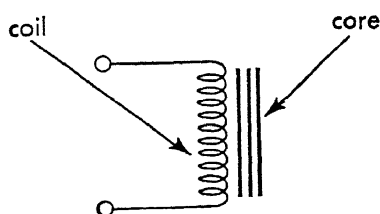


FIG. 4-25

Fig. 4-25 shows the schematic symbol for the electromagnet. It is the symbol for a coil combined with a symbol to indicate that the coil has a core.

USING THE ELECTROMAGNET

To operate your electromagnet, slide each end of the wire under one of the paper clips that hold the battery in your conductivity tester so that each wire is held in good contact with one of the terminals of the battery.

Figure out which end of your electromagnet is the north pole by applying the left-hand rule. Remember that electrons come out of the bottom of your battery and go back into the small cap. Test your conclusion with your compass.

Try picking up an iron or steel object, such as an empty Band-Aid box, with your electromagnet. While

the box is suspended in the air, disconnect one wire of the electromagnet. Since very little magnetism remains in the core, the box will fall.

Why the Coil Was Made as It Was

Here is how the coil of the electromagnet was designed. It was decided that the magnet should draw only $\frac{1}{4}$ ampere so that it could be operated continuously from one battery. (You will remember from Chapter 3 why $\frac{1}{4}$ ampere will permit continuous operation.) A $1\frac{1}{2}$ volt battery will force $\frac{1}{4}$ ampere through 6 ohms. The wire available for the coil is American Wire Gauge Number 30, which has a resistance of little more than $\frac{1}{10}$ ohm per foot. Fifty feet of it has 6 ohms resistance. Since this much AWG 30 wire will give about 400 turns around your core, your electromagnet will have about 100 ($\frac{1}{4}$ ampere times 400 turns) ampere-turns of magnetic force. Magnet wire, with its very thin insulation, was used because 50 feet give more turns than would 50 feet of wire with thicker insulation. If more than 50 feet had been used, there would have been more turns but more resistance and less current, so the result would have been about the same number of ampere-turns. If a finer wire had been used, fewer feet would have 6 ohms resistance, so there would have been fewer turns. Since the current would still have been $\frac{1}{4}$ ampere, there would be fewer ampere-turns. By the same logic, a heavier, longer wire would have given more ampere-turns. This is the kind of logical process that is used in the design of every piece of electrical apparatus—indeed, almost every manufac-

tured article is designed in the same thoughtful way to take best advantage of existing materials and get optimum performance by the most effective combination of several variables.

Measuring the Lifting Force of Your Electromagnet

You can measure how much weight your electromagnet will lift by adding pennies to an empty Band-Aid box until your electromagnet just can't lift it. A small Band-Aid box weighs very roughly 2 ounces, and 9 pennies weigh about an ounce. You can nearly double the lift of the electromagnet by connecting it to two batteries in series. However, don't leave it connected very long, because you will be drawing about $\frac{1}{2}$ ampere. You can make a two-battery holder for this and later uses by following Fig. 5-33 and the principles used in the construction of the battery part of the conductivity tester. The two clips used to make contact with the ends of the battery in Fig. 1-4 should be held down with nails $6\frac{1}{4}$ inches apart instead of $3\frac{3}{4}$ inches as in the figure. You will need 4 nails and a rubber band to hold each battery as in Fig. 1-7. Be sure to install the batteries with the cap of one against the base of the other, and the base of the first and the cap of the second against the bent paper clips.

Magnetic Lift for a Crane

You can attach your electromagnet to the hook of a toy crane and wire it to a battery holder inside the body of the crane. Mount a switch on the outside of the body and wire it in series. Then you can turn the electromagnet

on when you have the magnet touching pieces of iron or steel and you want to lift them and the magnet together, and you can turn it off when you want to drop the pieces. Steel mills and junk yards use huge magnets on cranes in this manner. They make it much easier to lift odd sizes and lots of small pieces without attaching hooks or first loading them into large containers.

In the next chapter other applications of electromagnets are examined to see how they are put to many important uses.

CHAPTER 5

MOTORS AND GENERATORS

We have seen how electricity can be used to produce light and heat. We have seen it used to indicate when events have occurred, to do computations, and to play games. We have seen how it can manufacture chemicals. We have seen it produce magnetism which can hold things while we lift them. Electricity is used for these purposes to serve some practical need.

In each case, however, there is some other means available to accomplish the same purpose. Heat can be produced by burning coal and oil. Modern lanterns burning kerosene and gasoline give excellent light. Mechanical indicators and computers are widely used. Most of the chemicals manufactured by electrical means can be manufactured by other processes as well. When electricity is used to do practical jobs, it is used because it is better—

cheaper, or more convenient, or cleaner, or safer, or faster.

If another means is better in enough of these ways, electricity is not used, but electricity is often best. It produces light and heat without your having to handle fuel, light it with a match, adjust burners, trim a wick, or clean a chimney. A kerosene heater uses up oxygen in a room, making it necessary to keep a window open and let in cold air, which absorbs much of the output of the heater. Electric heaters don't use oxygen. Electricity may produce a chemical at a lower cost or of a greater purity than by other means, or without byproducts for which there may be no market. Electric computers can do their work faster than mechanical ones. You will remember that a magnetic crane doesn't require a hook to be attached to its load nor do small pieces have to be loaded into large containers.

Electricity is often chosen to do a job, and it is chosen because it is best, but first there is always some practical job to be done.

One of the most important kinds of work in the world is moving things. We move trains, and furniture, and the hands of a clock. We move the beaters of a kitchen food mixer, and the car of an elevator, and the lever on a switch. We move the rotor of a water pump, and the clothes in a washing machine, and a phonograph record. There are many sources of power for making things move. Steam engines, gasoline engines, water power, and—by no means the least—manpower. But electricity can provide the

power to move things, and it is often the best choice. Let's see why.

SOME KINDS OF ENERGY

An object in motion has energy stored in it in a form called *kinetic energy*. This *energy of motion*, like all energy, has to come from somewhere. The kinetic energy in a book falling off a table is converted from another form of energy called *potential energy*, which was stored in the book while it was on the table. Potential energy is the energy stored in an object by virtue of its being at a height. The potential energy in the book was converted from the kinetic energy of the arms of the person who put the book on the table. The kinetic energy in the person's arms was converted by his muscles from *chemical energy* stored in the food he ate. (You have seen chemical energy converted directly to electrical energy in the battery you made.) The chemical energy stored in food was converted by plants from *light*—a form of energy—given off by the sun. All our fuels got their energy from the sun. Wood is a plant, and coal and oil and natural gas were formed from plants which converted sunlight into chemical energy.

In addition to fuels, an important source of energy for practical work is water power. The energy in water held in a dam is potential energy—like the energy in the book on the table. The water is accumulated rain, which came from clouds, which were formed by evaporation of water by the sun. (Atomic fuels are radioactive elements which

probably came from another star like the sun which exploded billions of years ago and, as a result, formed the planets.)

ENERGY AND WORK

In order to do the practical work of moving things, we have to convert the chemical energy stored in fuels or the potential energy stored in water into kinetic energy in the thing we want to move. Fuels are usually burned, their chemical energy thus being converted into *heat*, which is another form of energy. The heat can boil water to operate a steam engine, or it can expand gases (the chemical products of the burned fuel) to operate gasoline or diesel engines. The output of these engines is kinetic energy in their moving drive shafts. We can also produce kinetic energy in the drive shaft of a water wheel from the potential energy of water by running the water downstream or through a pipe from a dam.

The next problem is to get the kinetic energy of the drive shafts of the steam or diesel engine or the water wheel transferred to the thing we want to move. In a flour mill the drive shaft of the water wheel can be connected directly to the grindstone. A steam engine can turn a long shaft to which many machines in a factory can be connected by gears or belts. But imagine a gasoline or steam engine in place of the electric motor in an air conditioner, or a hand drill, or a food mixer. Or imagine a long thin shaft from a dam 10 miles away to the clock on your wall. There are the oil burner, and the hair drier,

and the electric fan. There are the movie projector, and the knife sharpener, and the electric refrigerator. There are the coffee grinder, and the blender, and the washing machine, and the sewing machine. There is even an electric motor in some toasters to raise and lower the bread. If kinetic energy could be produced only by gasoline or steam engines or by water wheels or by your own physical efforts, you would have to go through life without many of the conveniences that you take for granted every day.

You can see that one of the big advantages of electricity is that there need be no shaft between the thing we want to move and the machine which converts the chemical energy of fuel or the potential energy of stored water into kinetic energy. All that is needed at the place where the movement is desired is an electric motor large enough to do the job. The energy can come through wires from a distant place, where the water is stored or the fuel is burned.

The central electric power station offers another great advantage. Small gasoline and diesel engines and small steam boilers are less efficient than large ones; they waste much of the stored energy of fuel in converting it to kinetic energy. Instead of converting its own fuels to drive its machines, a small factory can buy energy for much less money from a large and efficient central power station, even though the kinetic energy produced in the engines has to be changed to electrical energy by means of generators and back to kinetic energy by motors. And

the electric current is the only practical means of transferring energy from a dam to the place where work has to be done.

Even before there were electric motors, inventors envisioned these advantages of using electricity to move things. The question was how to make electricity produce motion. To move very light, small objects, the force of electric charge is sufficient. A comb charged by running it through your hair will lift tiny scraps of paper. We have seen this force move ions around inside an electrolyte; the same force of attraction between unlike charges is used to cut down the smoke of factory chimneys by moving the smoke particles out of the exhaust gases and thus reducing air pollution. But inventors discovered that for most practical purposes motion could best be produced by electricity as it works through the medium of electromagnetism.

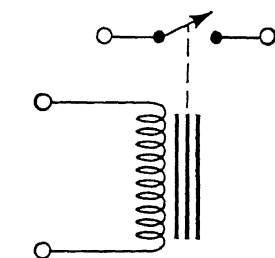
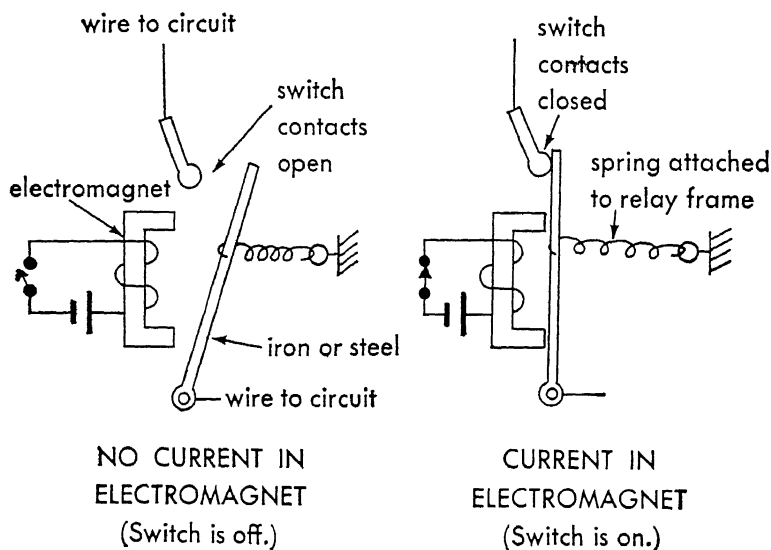
If it is to produce motion efficiently, magnetism must be applied in carefully arranged ways. You can't simply put an electromagnet on one side of a room and a piece of steel on the other and expect them to fly together when the current is turned on. So before we see how magnetism is put to work inside a motor, let's look at an important but simpler device called a *relay*, in which electromagnetism produces motion.

THE RELAY

A relay is nothing more than a switch which is operated not by your hand but by an electric current. A simplified

MAKING ELECTRICITY WORK

relay is shown in Fig. 5-1 so you can see how it operates. (Note that the schematic symbol consists of a combination of the symbol for an electromagnet and the symbol for a switch.) When the current flows through the electromagnet, the magnetic force closes the switch. (This is indicated in the schematic symbol by the broken



SCHEMATIC SYMBOL

FIG. 5-1

line.) When the current is turned off, a spring pulls the switch back to the off position. To understand the operation of the relay, you must note two important points. First, the circuit of the electromagnet and the circuit of the switch are *not* connected electrically. This means that the magnet requires only enough current and voltage to move the switch; the switch itself can be built to be used to open or close circuits carrying much greater currents at much greater voltages. Second, the switch which supplies power to the electromagnet can be at a distance from the relay.

Before we build a relay, let us look at some specific applications. These will illustrate several general situations in which relays can be used today in industry or in the home.

Remote Switching

In every central power station there are many generators which must be switched onto and off the power lines as the use of current increases and decreases during the day. The generators produce huge currents at high voltages. The mammoth switches required are too big and heavy, and the voltages they handle are too high, to permit them to be operated by hand. Moreover, these switches must be placed at widely separated places around the power station, but to prevent switching mistakes, which would be costly and dangerous, it is important that all switching be controlled from one central location. For these reasons, big relays are used to do the switching, as

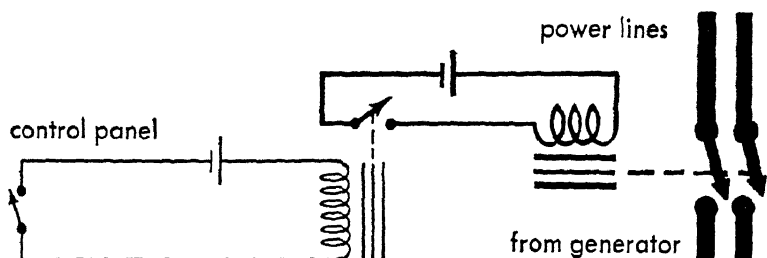


FIG. 5-2

in Fig. 5-2. Because of their size, even their magnets require heavy currents—although not nearly so heavy as their switch contacts can handle—and fairly big switches are needed to operate the relays themselves. Because even these switches are too big to fit on the control panel, additional relays, smaller than the first ones, are used. The switches to operate these smaller relays *do* fit on the control panel.

The same sort of use for relays is found at the other end of the power line wherever large motors are employed. The motor requires heavy wiring. It would be expensive and cumbersome to detour these heavy wires to a point from which it would be convenient to control the operation of the motor, and then install a heavy switch at that point. Instead a relay is placed at the motor, and the heavy wires are run direct. Then light wires to carry the current to operate the relay are run to a small switch at the control point. You can see how important this is if many motors are to be controlled from one point.

The oil burner in your own house is turned off and on by a thermostat—that is, a temperature-operated switch located in some part of the living area. The thermostat

operates a relay which switches on the oil burner. A much smaller thermostat can operate the relay than would be required to operate the oil burner directly, and it can be made inconspicuous. The use of the relay also saves running heavy wires from the basement to the thermostat in, say, the living room, and then back to the basement.

Tiny Currents to Control Large Ones

Another application of the relay permits a very weak source of power to be used to start or stop a heavy current. One kind of photoelectric cell produces a small voltage when light falls on it. The small current generated by the cell can be made to operate a very sensitive relay whose contacts are big enough to close the circuit of a larger relay, which can, in turn, operate other electrical equipment in response to changes in light. For example, street lights can be turned on automatically when the sensitive photoelectric cell "sees" that it is getting dark.

Simplifying Complex Circuits

A self-service elevator employs a number of complex control circuits. It must be possible to call the elevator from each floor. The elevator has to trip a switch and stop itself when it arrives at the right floor. When it is stopped—and only then—it has to run a motor to open its own door. When the passenger is inside, he presses a button to send the car to a new floor, but the car cannot move until it has closed its own door. If, on its way, there is a waiting passenger, it has to stop for him. And there are many other functions.

If each button or trip switch had to turn the elevator motor on or off, each would have to be very large to handle the heavy current, and the heavy power cables would have to be routed down the car's supporting cables to each of the buttons inside the car and around the building to the switches on each floor. The use of relays permits these switches and wires to be conveniently small. Of course, there is a lot more to controlling an elevator than turning the motor on and off. For instance, when a person rings for the elevator, he doesn't want to have to keep the button pressed until the car arrives. Instead a relay "remembers" where the car was called. When the car finally arrives, the relay is made to "forget" and is readied to "remember" a new call. When you build your relay, you will learn how to make it "remember."

BUILDING A RELAY

Now that you understand some of the many uses for relays, you can build one which you can put to still other uses. Start by cutting a strip of coffee can (see Fig. 4-2) for the core $\frac{1}{2}$ inch wide by 11 inches long. Bend the strip as in Fig. 5-3*A*, using a pair of pliers to start the first bend straight along the bend line. Then fold the first bend the rest of the way by hand (*B*), being careful not to cut yourself. Finally squeeze the bend tight with pliers (*C*). The second and third bends (*D* and *E*) are made all the way with pliers. Bend number four (*F*), like the first, is started with pliers, completed by hand, and finally squeezed tight with pliers. The last two bends (*G* and *H*) are made by hand.

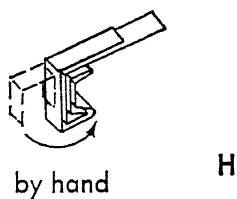
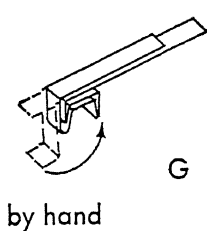
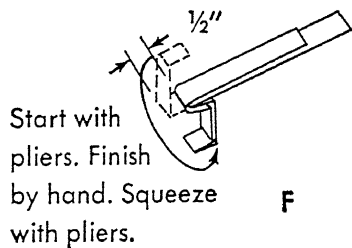
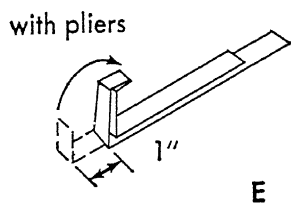
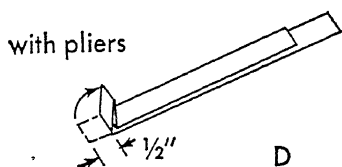
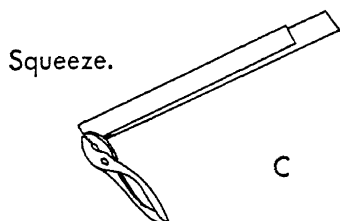
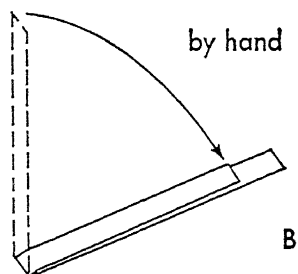
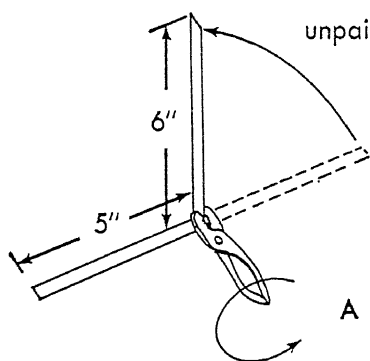


FIG. 5-3

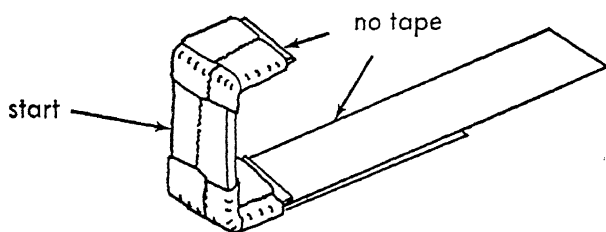


FIG. 5-4

Wrap the core with Scotch Tape as in Fig. 5-4 so that none of its edges will cut into the enamel insulation on the magnet wire when you wind the coil. Since the springiness of the steel tends to make the core open up slightly, start with a piece around the 1-inch-long 4-layer-thick part as indicated in the figure, to hold the layers together.

Select a piece of wood at least $\frac{1}{2}$ inch by 2 inches by 3 inches. Drive two upholsterer's nails nearly all the way in at the points shown in Fig. 5-5. Then slide one end of

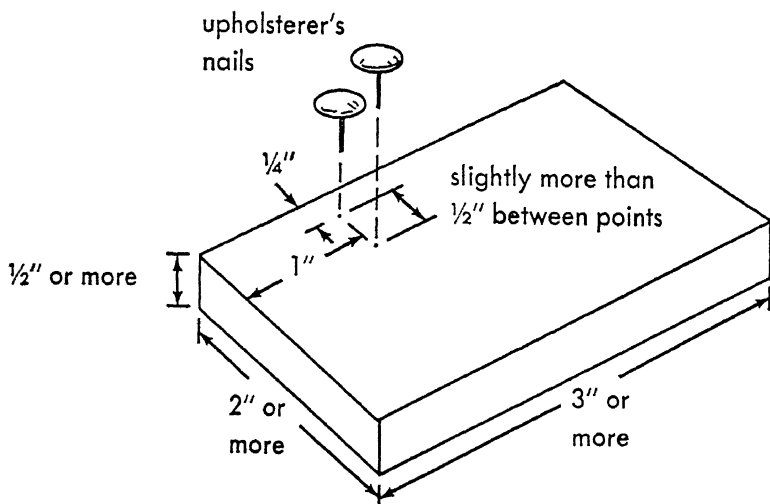


FIG. 5-5

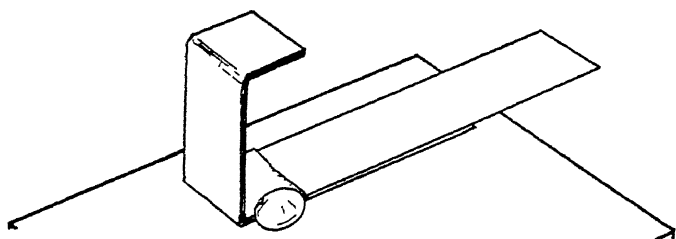


FIG. 5-6

the core under the nail heads as shown in Fig. 5-6 and drive the nails all the way in to hold the core. Wind 50 feet of magnet wire on the core, leaving 1-foot ends, following the directions on page 125, as you did in making the electromagnet.

Now cut a piece of bell wire 4 inches long and remove its insulation. Lift the longer, upper end of the core, which will be the moving arm, as in Fig. 5-7, and wrap the bell wire around it as shown. The wire will be the common

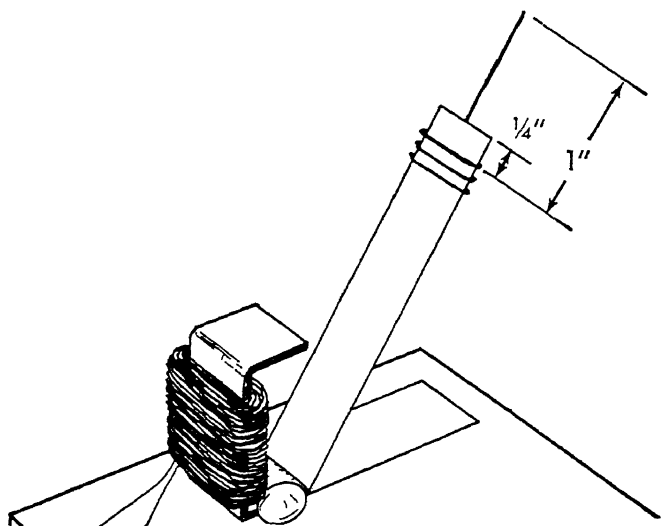


FIG. 5-7

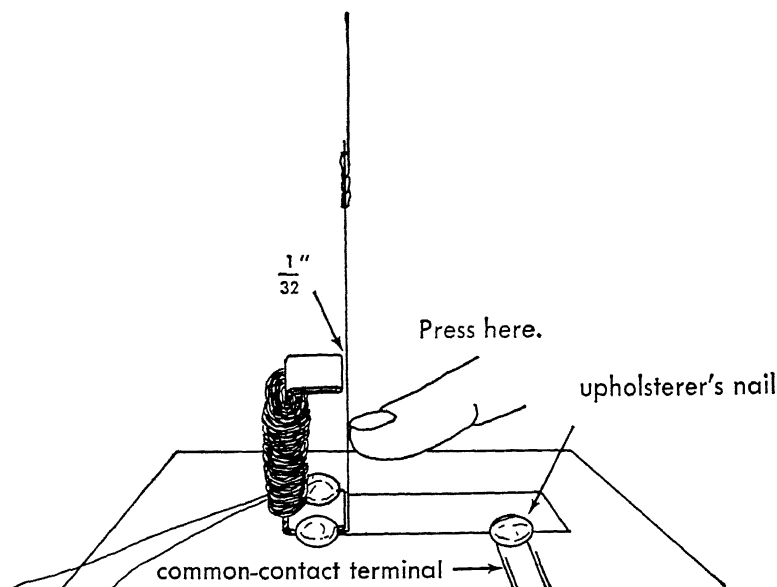


FIG. 5-8

contact of the switch part of the relay, like the moving paper clip in the single-pole double-throw switch in Fig. 2-10. Crush the turns tight to the core with pliers to insure a good electrical and mechanical connection. Bend the moving arm up until it is $\frac{1}{32}$ inch from the upper end of the core, as in Fig. 5-8. To do this you will have to press hard enough at the point shown so that after you let go and the moving arm springs back, it leaves a gap of $\frac{1}{32}$ inch. Make sure that the arm is $\frac{1}{32}$ inch away all along the upper edge of the core. If not, twist the arm so that the sides of the gap are parallel. Drive an upholsterer's nail over a paper clip as shown in Fig. 5-8 to make a terminal for the common contact. (Use your conductivity tester to see that this paper clip terminal and the common-

contact wire on the moving arm are actually connected electrically through the moving arm.)

Now you are ready to make the other contacts of the switch part of the relay. Your relay is going to be a single-pole double-throw type—that is, it will switch a wire from one circuit to another. Start with a piece of wood at least $\frac{1}{4}$ inch by 3 by 5 inches. Bend two paper clips and, using upholsterer's nails, mount them together with two other clips, as shown in Fig. 5-9. Add a third nail and a paper

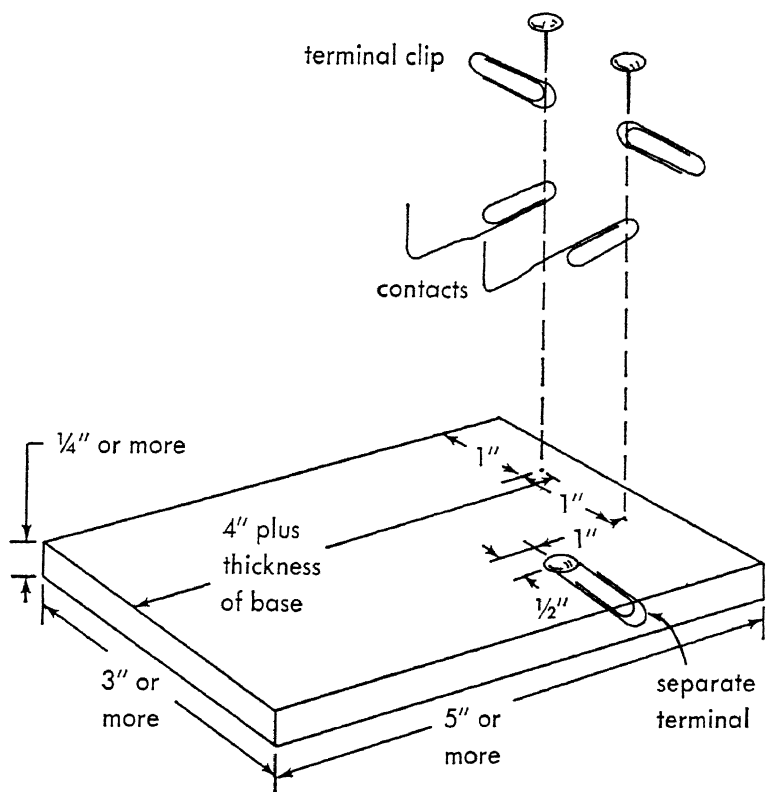


FIG. 5-9

clip to be used as a separate terminal for later work. Finally join the two pieces of wood together as in Fig. 5-10.

Adjustments

The contacts must now be carefully adjusted. The contact on the right in Fig. 5-10 is called the *normally closed* contact because the common contact will touch it when no current is flowing in the coil. The contact on the left is called the *normally open* contact because the common contact will touch it only when current is flowing through the coil. (In schematic diagrams the common contact is *always* shown touching the normally closed contact.) Bend the normally closed contact so that it presses against the common contact on the moving arm and pushes it toward the core until the $\frac{1}{32}$ -inch space between the upper end of the core and the moving arm after you let go is reduced by half. (If you bend the contact too far, bend it back and start over.) The common contact and the normally closed contact are held together by their springiness so as to make a firm connection.

To adjust the normally open contact, press the moving arm over, without bending it permanently, until it touches the upper end of the core. Now bend the normally open contact until it touches the common contact on the moving arm, and then bend it a little farther so that when the moving arm is pulled over by the electromagnet, both the common contact on the moving arm and the normally open contact will be bent slightly against their springiness. This will make for good electrical contact, and it will also serve another purpose. Since the relay core is

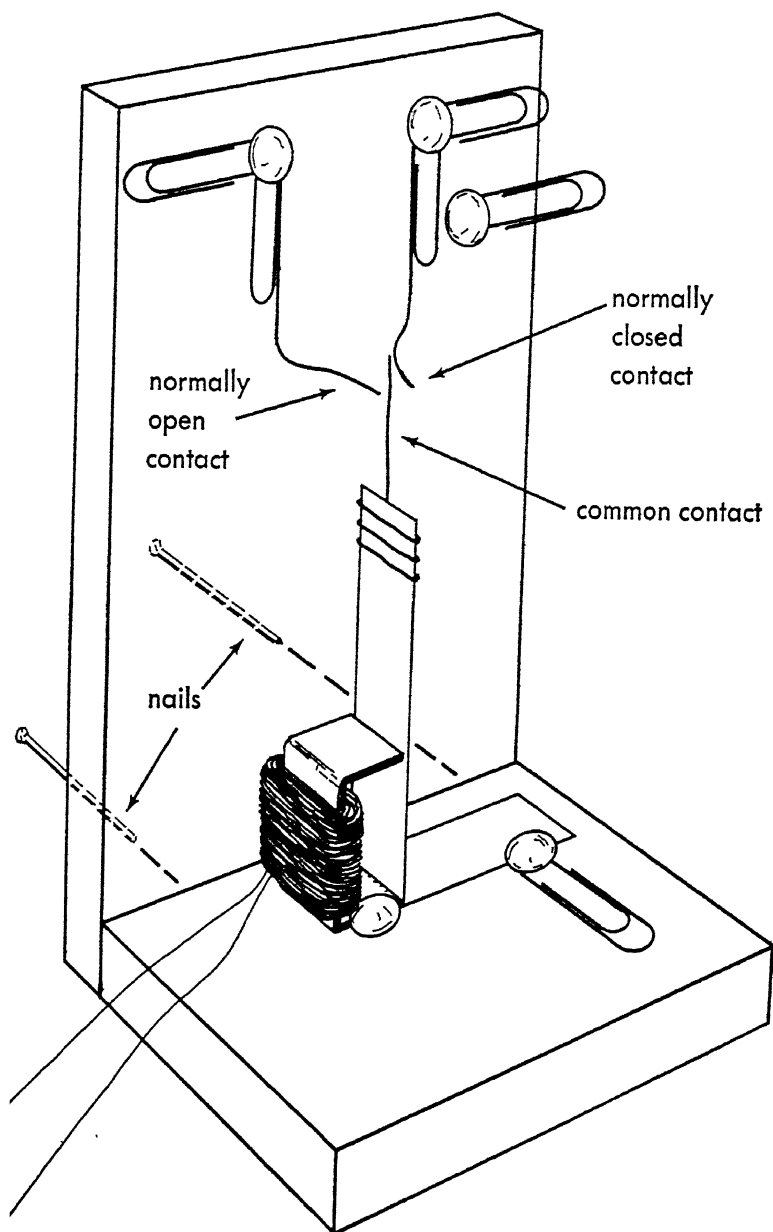


FIG. 5-10

made of coffee-can steel, it will become a weak permanent magnet once the coil is energized. Its permanent magnetism may be strong enough to hold the moving arm to the core when current is turned off in the coil. When you have adjusted the normally open contact properly, it will exert a force on the moving arm which will aid its own springiness in overcoming the permanent magnetism. This extra force is exerted only until the common contact and normally open contact separate. It doesn't work against the electromagnet when we don't want it to—when it is first turned on the magnet's pull on the moving arm is weakest because the air gap is at its largest.

In designing the relay, we might have made the moving arm longer so that it could act as the common contact instead of the copper wire. But when the relay is operated, tiny sparks jump between the contacts as they are opened, and these sparks cause the contact surfaces to oxidize and develop high resistance when they should be making good low-resistance contact. (You will have to clean the contacts carefully from time to time with fine sandpaper.) The oxidation process seems to progress more slowly with paper clips touching copper wire than with paper clips touching coffee can. If you study metallurgy in college, you may want to do a research project on why this is true. Commercial relays usually have contacts of a special silver alloy which does not oxidize and hence never needs cleaning or they clean themselves by rubbing together.

Test your relay by connecting your conductivity tester between the normally closed contact terminal and the common terminal. The tester bulb should, of course, light.

Then connect a separate battery to the relay coil. The moving arm will be attracted to the magnet, and the tester bulb will go out. Shift the lead of the conductivity tester from the normally closed contact terminal to the normally open contact terminal, and the bulb will again light. Now disconnect the coil from the separate battery, and the bulb should again go out. If all these actions do not occur, examine the relay carefully and readjust the contacts and moving arm if necessary.

You can see that the relay design fulfills two of the requirements for efficient magnetism. The coil is the same as that of your electromagnet; thus you will have 100 ampere-turns producing magnetism (see page 122) when you use your 1½-volt flashlight battery. You also have a low-resistance path for the magnetism: four thicknesses of coffee can through the coil and the two legs, a thickness in the moving arm, and a very small air gap. Of course, bigger relays could have many thousands of ampere turns and a much thicker iron or steel path for the magnetism. Your relay was designed as it was to use available materials. One advantage of the design is that coffee-can steel is springy, and therefore you don't need a separate spring to return the moving arm to the normally closed contact.

USING YOUR RELAY

Now that your relay is working, you can connect it to the open-door indicator you made in Chapter 2 so that the circuit will "remember" and "forget" when the door has been opened. When you understand the circuit

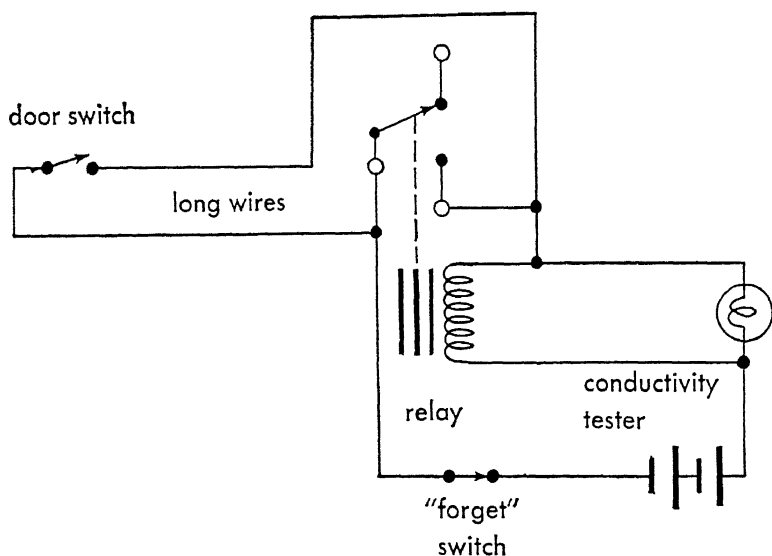


FIG. 5-11

shown in Fig. 5-11 you will be able to see that it has advantages over your previous open-door indicators.

The circuit includes your signal-while-door-is-open switch (Fig. 2-5). Trace the schematic and you will see that when the contacts on the door switch are closed—because the door has been opened—the bulb will light. But since the coil of your relay will also be energized, the common contact and the normally open contact of the relay will close. Now if the door is closed again the bulb will remain lit, this time through the relay contacts. Trace through the schematic to see how the current flows to keep the coil energized. The intruder can do nothing to turn off the light unless he sabotages the relay or opens the “forget” switch, which are hidden in your room. You can turn off the light by opening the “forget” switch,

which de-energizes both the bulb and the relay. When you close the "forget" switch again, the bulb will remain off until the door switch is closed by the door's being opened again. Another advantage of this circuit is that you can reset it without approaching the door and calling attention to the door switch.

This "memory" circuit and the one in the self-service elevator do much the same thing.

| | OUR CIRCUIT | ELEVATOR CIRCUIT |
|--|--|---|
| <i>Information retained:</i> | Door was opened. | Waiting passenger pushed button. |
| <i>Reason for retaining information:</i> | Door can be closed again. | To permit waiting passenger to release button. |
| <i>Method of retaining information:</i> | Lighted bulb. | Complex circuits in elevator. |
| <i>Information retained until:</i> | Light is seen and "forget" switch is opened. | Car is ready to act on information and approaches floor and operates trip switch. |

THE BUZZER

There are many other applications of relays. Perhaps the most common one of all is the ordinary doorbell or

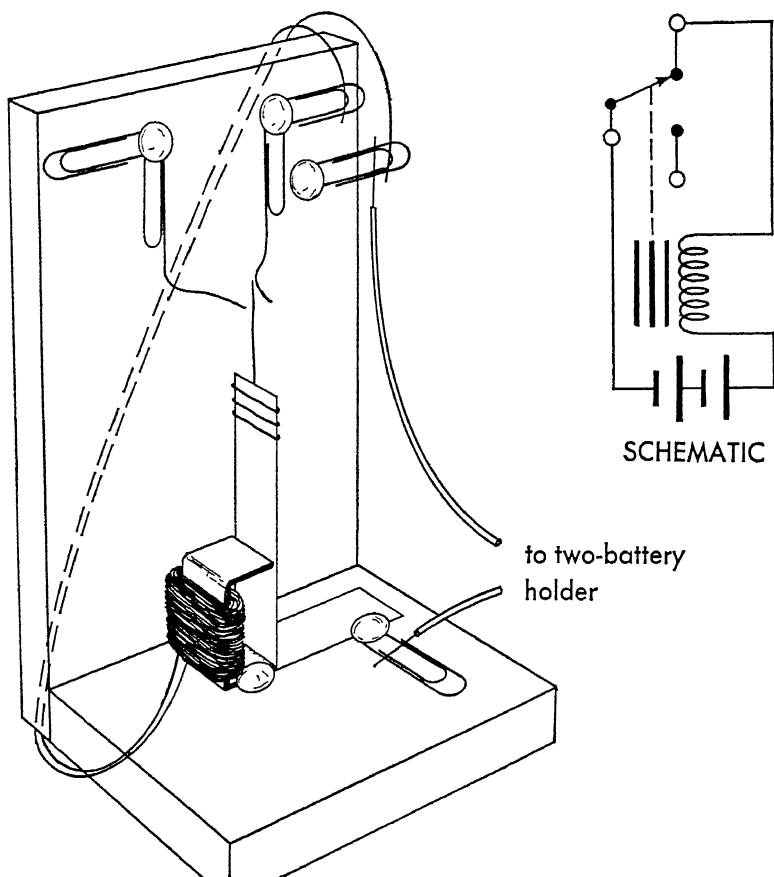


FIG. 5-12

buzzer. You can convert your relay into a buzzer by connecting it as shown in Fig. 5-12.

You can see from the schematic that when the switch is closed, the relay coil is energized. As soon as it is energized, the moving arm begins to disconnect the common contact from the normally closed contact. The arm has to move some small distance before the contacts separate,

but when they do, the circuit is broken. The moving arm continues to move a further small distance under its own momentum, but it is no longer attracted by the electromagnet because the electromagnet has been de-energized. The springiness of the moving arm soon stops it and returns it to the starting position, where the contacts again close and the whole cycle is repeated. The cycle from closed to open to closed again is very rapid, occurring at the rate of about 300 times per second. The moving arm vibrates the whole framework of the buzzer and all of these moving parts create vibrations—that is, sound waves—in the surrounding air. The number of times per second, and therefore the pitch of the buzzer's sound, can be adjusted, as in all buzzers, by changing the tension on the contacts.

You can estimate the vibration of your buzzer by trying to match its pitch with that of a particular piano note. It will probably be close to the pitch of one of the following notes:

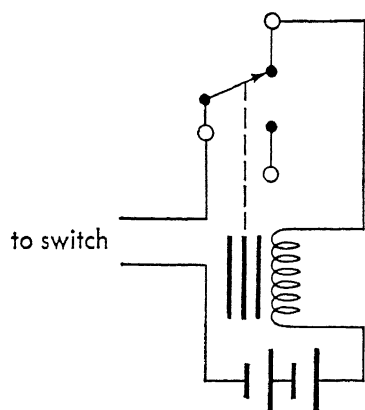
Note: Middle C D E F G A B C

Vibrations

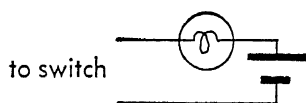
per second: 262 294 330 349 392 440 494 524

Each note in the scale has twice the vibrations of the same note in the octave below.

Because the buzzer circuit remains closed only part of the time, and because it takes a tiny but measurable fraction of a second for the current to build up in the coil, the average current is less than $\frac{1}{4}$ ampere. For this reason the magnetism is weaker than when the relay is operated



THE BUZZER



THE CONDUCTIVITY TESTER

FIG. 5-13

on steady current. The magnetism is also weaker because the air gap between the moving arm and the magnetic loop is almost never closed; hence two batteries (see Fig. 5-33) are needed to make a sound that is adequately loud. If you place the buzzer on top of an empty coffee can, the sound will be amplified.

You can use the battery and buzzer combination in place of the conductivity tester in some of the circuits you constructed in Chapter 2. In the penny-pitch, the game with the stair-light circuit, and the unanimous voting machine, the buzzer will give you an audible instead of a visual indication as in Fig. 5-13. Then you won't have to keep your eye on the bulb.

MOTORS

Building the relay has shown you one way of using electricity to produce motion. A relay doesn't produce

much motion, but the motion that is produced is useful for many practical purposes. Many other practical purposes require considerably more motion. The motion required may be rotary, as in an electric fan, or along a line, as in an elevator or an electric train. Obviously we can't put an electromagnet at the top of an elevator shaft and expect the steel elevator to rise to the top of the shaft when the magnet is turned on. Six floors of air gap in the magnetic circuit would have so much reluctance that the magnet would have to be impossibly powerful to lift a tiny elevator, or for that matter even a paper clip. For the same reason we can't expect a magnet in Chicago to pull a train in New York. To get motion along a line directly from magnetism, we would have to design a much more intricate arrangement. But a motor, which produces rotary motion, can lift an elevator by winding its cables around a drum, or can drive a train by turning its wheels. Let's see why a rotary motor—in addition to being obviously suitable for rotary motion, as in fans—is much more suitable for producing motion along a line than some intricate arrangement for producing it directly.

Suppose you wanted to move a small car along a track. You could station a man every 2 feet along the track who, as the car approached, could give it a push. You would need 50 men for every 100 feet the car traveled, and each man would work for only a few moments each trip. Now suppose you had a rope running along the track, and one man on the car pulled himself and the car along by pulling on the rope. In this way only one man working steadily would be required, and, if the car wasn't too

heavy and the wheels had easy-to-turn bearings, the scheme would work well. Note that he would have to pull hand-over-hand in a constantly repeating pattern, the movement of his hands being essentially similar to rotary motion.

Any scheme with magnets all along the railroad tracks or along the sides of an elevator shaft would be impractical, because there would have to be so many magnets that the cost would be prohibitive. But, as you know from your everyday experience, rotary motors *are* both practical and economical. In order to see why, let us first see how they work; then we will build one.

HOW A MOTOR WORKS

Fig. 5-14 shows a highly simplified picture of a motor. (In a working motor, the shaft would have to be supported at the ends so that it could only rotate and not move in any direction, but the shaft supports have been left out so that we can see the workings more clearly.) Apply the left-hand rule (see Fig. 4-19), observing the way the coils are wound and the battery is connected. You will see that the upper end of the *rotor* (the part that turns) would be a north pole, as would the left-hand end of the *stator* (the part that stands still). Since the shaft can rotate, magnetic attraction (of unlike poles) and repulsion (of like poles) will swing the rotor around so that it will line up horizontally between the two poles of the stator, twisting the lead wires as it does so.

When the rotor is lined up with the poles of the stator, it will continue to move by its own momentum. But when the ends of the rotor pass the center of the poles of the

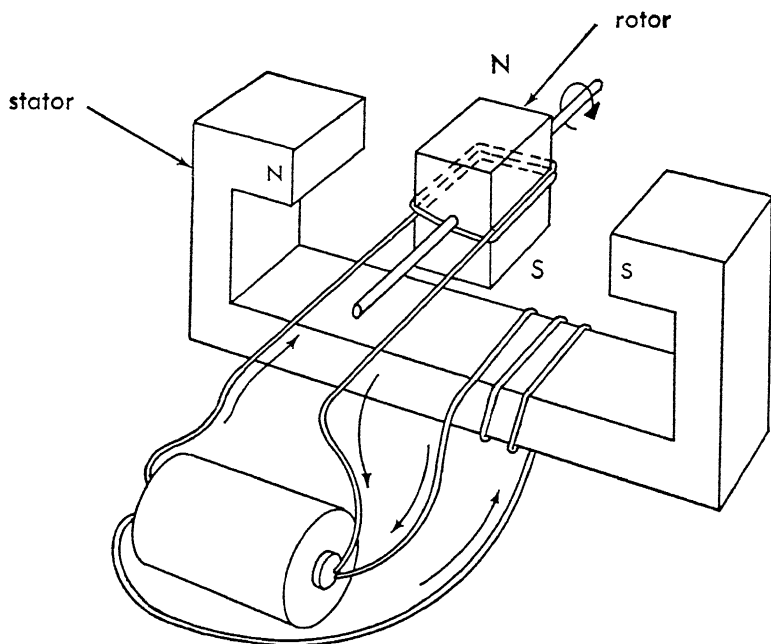


FIG. 5-14

stator, they will swing back, attracted by the magnetism of the stator, and eventually come to rest lined up horizontally.

Providing, as it does, only a quarter turn of rotation, this motor is obviously more useful in teaching motor principles than in producing rotation.

The Commutator

What is needed to make the shaft rotate continuously is some arrangement to disconnect the coil of the rotor when it is nearly lined up horizontally, and then reconnect it so that current flows in the opposite direction through the coil soon after it has swung beyond the horizontal posi-

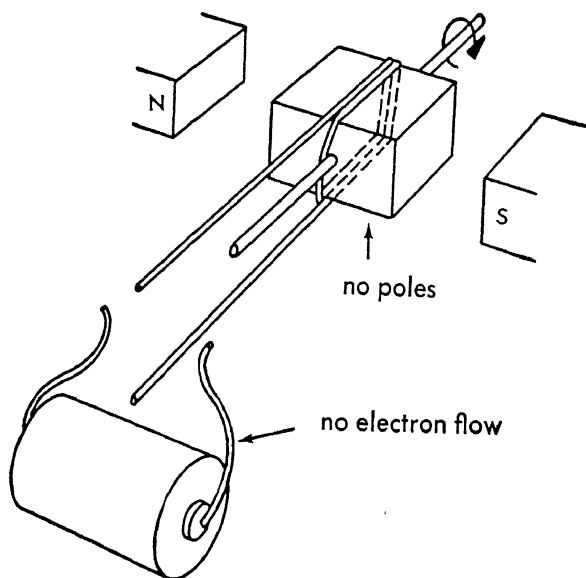
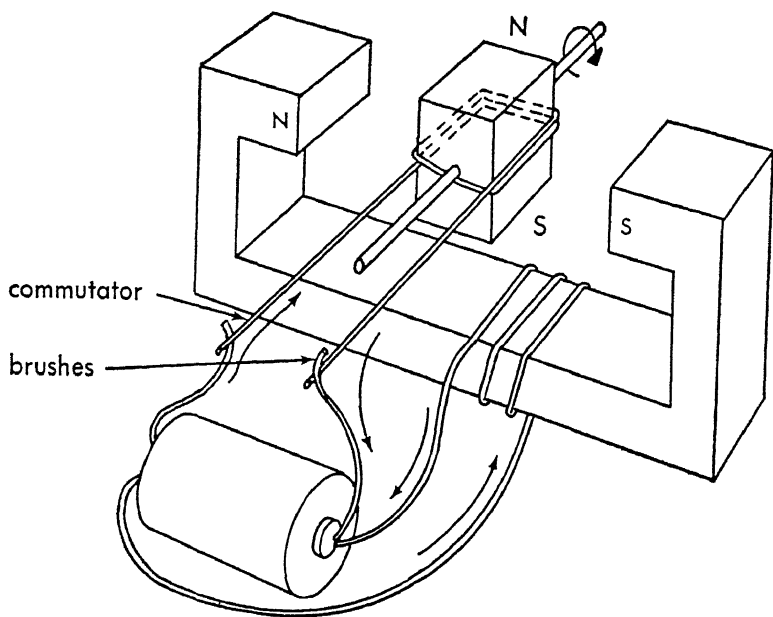


FIG. 5-15

tion. This reversal of current will reverse the poles of the rotor. The end of the rotor near the right-hand end of the stator (Fig. 5-14) will continue to move by momentum and by its new repulsion for that end of the stator. The arrangement must then re-reverse the rotor connections when the rotor is again nearly horizontal.

Fig. 5-15 shows such an arrangement, which is called a *commutator* and *brushes*. When the rotor is spun to start it, the uppermost end will always be a north pole except for the period during which the ends of the coil have left the brushes and are moving around toward the opposite brushes as the ends of the rotor pass the poles of the stator.

BUILDING A MOTOR

You can build a motor that will operate in just this way. Start by cutting strips of coffee-can steel as shown in Fig. 5-16. (Refer to Fig. 4-2 to remind yourself how to cut

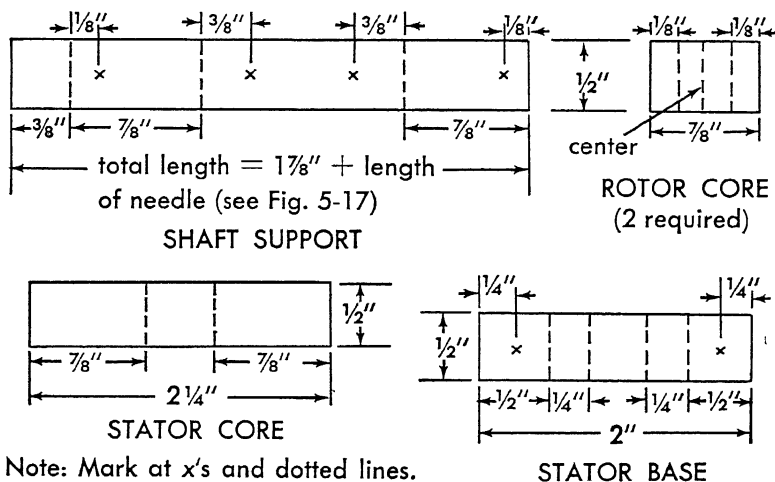


FIG. 5-16

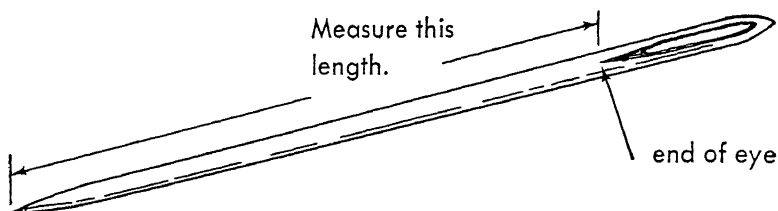


FIG. 5-17

up a coffee can.) The length of the shaft support in Fig. 5-16 will depend on the length of the darning needle you will use for the shaft of the motor. Find one at least 2 inches long and measure from its point to the spot near the eye where the shaft of the needle stops being smooth and round, as shown in Fig. 5-17. Add $1\frac{7}{8}$ inches to this measured length, and that is the length you should cut the shaft support.

Mark all the pieces at the lines indicated in Fig. 5-16. Lay the shaft support and the stator base, unpainted side up, on a piece of scrap wood and puncture them with an upholsterer's nail and hammer at the six places marked X.

The Shaft

Using a pair of pliers, bend the shaft support at the lines you have marked on it to the shape shown in Fig. 5-18. The end marked "thrust bearing" in Fig. 5-18 must be bent quite carefully. The last $\frac{1}{8}$ inch must be at right angles to a line through the two holes, one in each shaft support. To see that it is, slip the needle through the two holes so that the point comes up against the inside of the thrust bearing, and check by eye that the needle and

thrust bearing are at right angles to each other. Now mount the shaft support with upholsterer's nails on a wooden base as shown in Fig. 5-18.

Find a small glass bead that the darning needle will pass through at least as far as the eye. The hole in the bead should not be very much larger than the needle, but it does not have to be a tight fit. Pass the needle, point first, through the hole in the straight shaft support, then through the bead, and then through the hole in the shaft

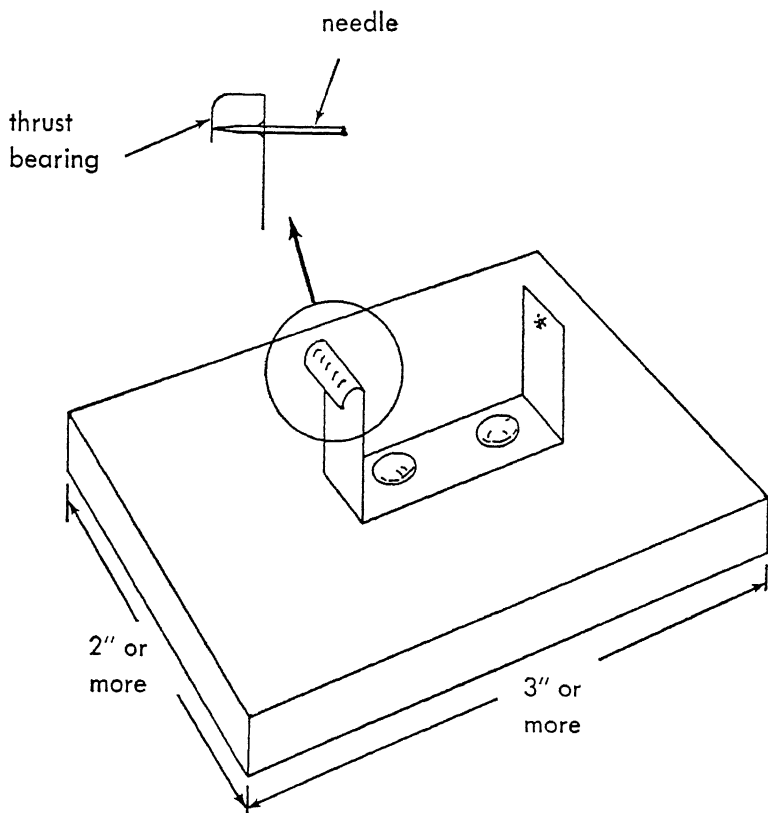


FIG. 5-18

MAKING ELECTRICITY WORK

support with the thrust bearing, as in Fig. 5-19. Cut a piece of Scotch Tape 1 inch long and $\frac{1}{8}$ inch wide. Making sure that the needle point is touching the inside of the thrust bearing, slide the bead up against the straight shaft support and wrap the piece of tape around the needle up against the bead to hold it against the straight shaft support. Now the shaft (darning needle) cannot move forward or backward but can only rotate.

Remove the shaft by bending the two shaft supports apart against their own springiness as in Fig. 5-20. (Don't bend them so hard that they stay bent.)

Cut a piece of Scotch Tape 1 inch long and $\frac{1}{2}$ inch wide and wrap it around the shaft as in Fig. 5-21. One edge of this piece should butt up against the piece holding the bead. Bend up the ends of the two rotor-core pieces at right angles as shown in Fig. 5-22. Cut two pieces of

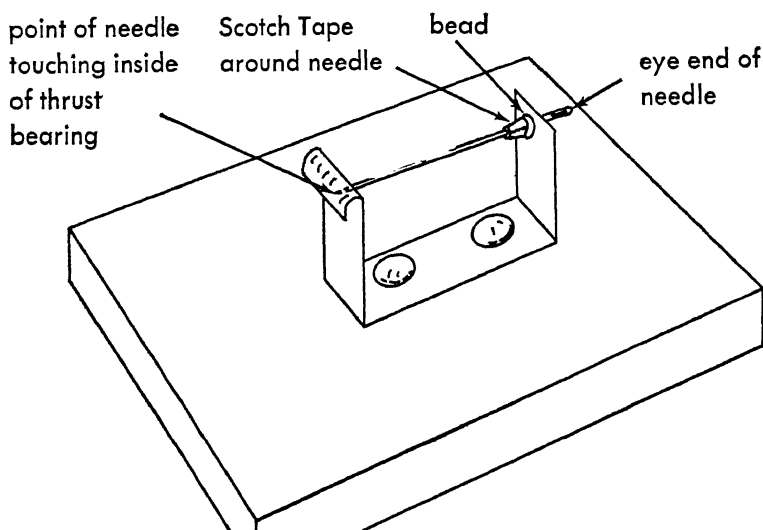


FIG. 5-19

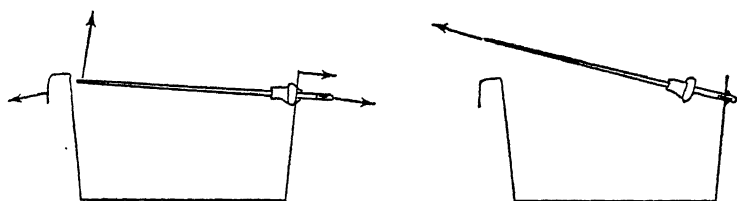


FIG. 5-20

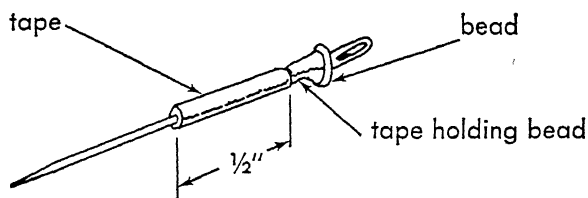


FIG. 5-21

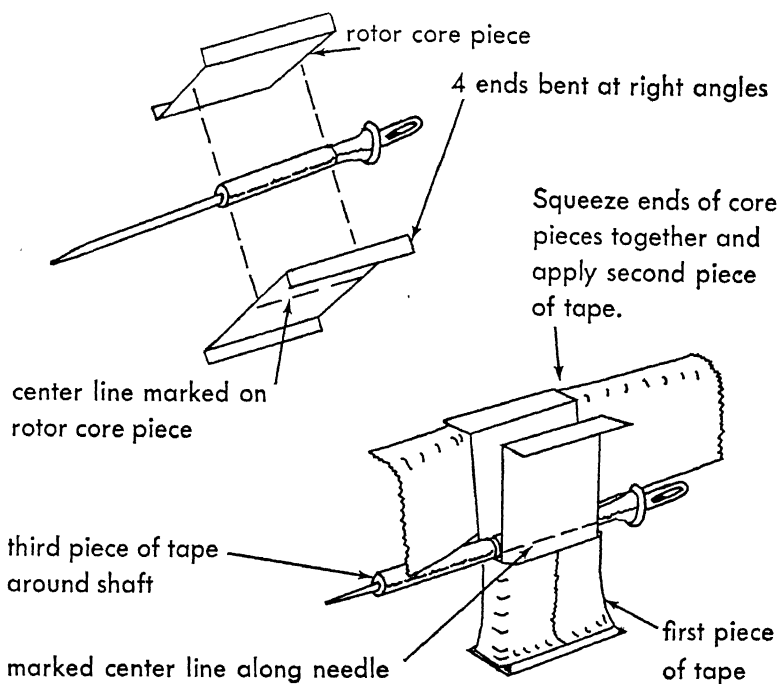


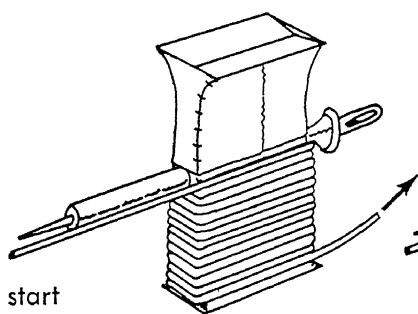
FIG. 5-22

Scotch Tape $1\frac{1}{2}$ inches long and $\frac{1}{2}$ inch wide and use them to tape the rotor-core pieces together, as in Fig. 5-22. The line you marked on the center of each core piece (see Fig. 5-16) must be lined up along the shaft so that the rotor will be balanced. Apply one piece of tape first; because of the thickness of the shaft, the two opposite ends of the core pieces will be held apart. Squeeze them together and apply the second piece of tape. In addition to holding the core pieces together around the shaft, the tape will prevent the core from cutting into the enamel insulation on the wire when you wind the rotor coil. Cut another piece of tape 1 inch long and $\frac{1}{2}$ inch wide and wrap this third piece around the shaft next to the rotor-core pieces.

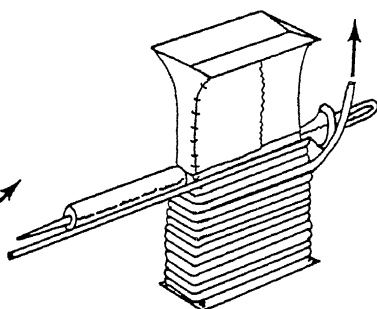
The Rotor Coil

Now you can begin to wind the rotor coil. Cut a piece of magnet wire 10 feet long. Hold 1 inch of the end against the last piece of tape applied, as shown in Fig. 5-23, and begin to wind as follows. Work down evenly to one end (*A*) and then work back to the shaft (*B*) and cross over to the other side. Do not change winding direction as you pass the shaft; if you do, the magnetism of some of the turns will oppose the magnetism of the others. (Fig. 5-23C shows how *not* to wind the wire.) Wind down the other side and back to the shaft again (*D*). Distribute what wire is left symmetrically on either side of the shaft. End up near the shaft with at least a 1-inch end (*E*).

Cut two pieces of Scotch Tape 2 inches long and $\frac{3}{8}$

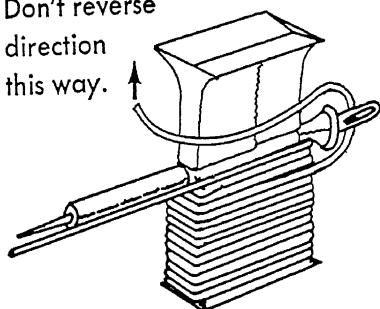


A

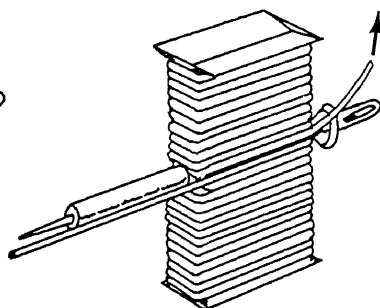


B

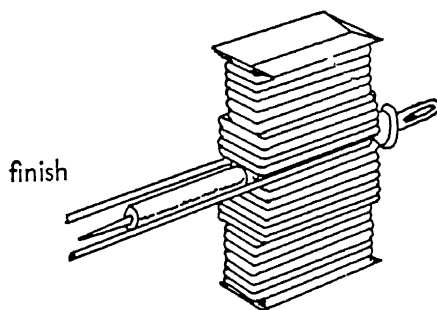
Don't reverse
direction
this way.



C



D



E

FIG 5-23

inch wide and wrap them around the winding as in Fig. 5-24.

The Commutator

Fig. 5-24 also shows the construction of the commutator. Run the two ends of the coil along the shaft toward the pointed end. Trim the two wires both off 1 inch from the edge of the coil nearest the pointed end of the shaft. Then, $\frac{1}{2}$ inch from its end, bend each wire back double. Line up each doubled wire carefully as in Fig. 5-24, so that when the rotor coil is *vertical* each doubled wire is on one *side* of the shaft. Cut two strips of Scotch Tape 1 inch long and $\frac{1}{8}$ inch wide. Wrap one strip of tape around the two wires and shaft right next to the coil.

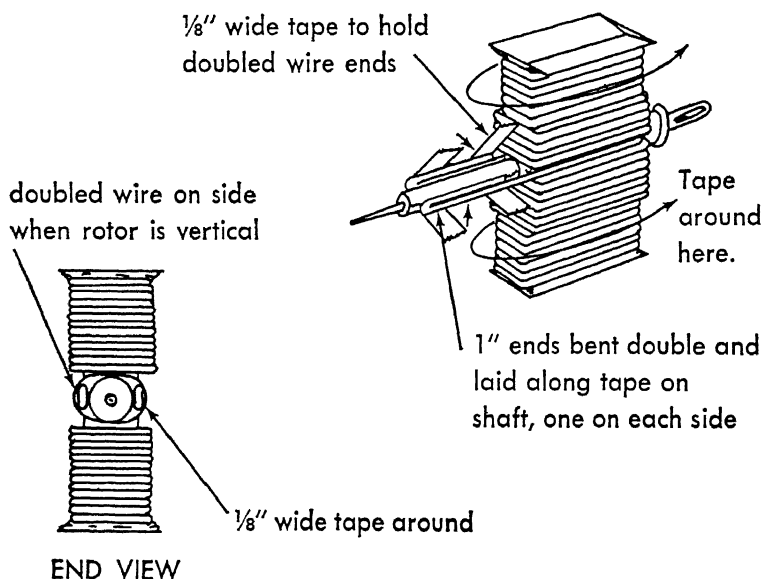
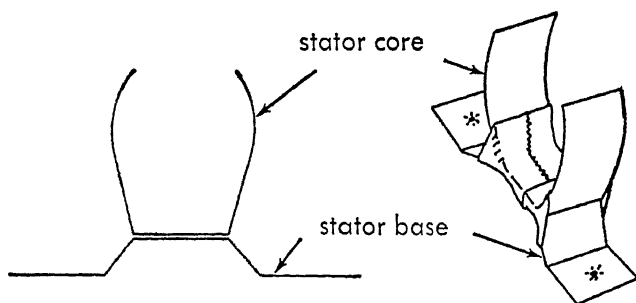


FIG. 5-24

Then, right at the end of the tape they are resting on (which you wrapped around the shaft earlier), wrap the second strip of tape around the two wires and shaft at the bend in the wires. With fine sandpaper, clean off the enamel from the part of each double wire which is exposed between the two $\frac{1}{8}$ -inch-wide strips of tape.

Place the rotor back in the shaft supports, following the reverse of the procedure shown in Fig. 5-20. The rotor must be able to rotate freely. The two shaft supports should not be so close together that the straight one presses against the bead, which in turn pushes the point of the shaft against the inside of the thrust bearing. This will add friction and make the shaft hard to turn. The way to check this is to touch your finger against the eye end of the needle. The bead should move very slightly away from the straight shaft support before the point of the needle touches the inside of the thrust bearing. Then pull lightly on the eye end of the needle. The point of the needle should move away from the thrust bearing before the bead touches the straight shaft support. You don't need to see what is happening; if you do the two steps in rapid succession you can feel and hear the results. This free movement of the shaft along its length is called *end play*. There must be some, but the less the better; $\frac{1}{32}$ inch or less is good. If there is no end play, bend the shaft supports slightly apart. If there is too much, remove the shaft and then bend the shaft supports so that when you let go they stay slightly closer together. Replace the shaft and check its end play again. Now put a tiny drop of light oil on the bead where it touches the shaft sup-

FIG. 5-25



port, and on the shaft where it passes through each shaft support.

Spin the rotor several times with your finger. If the rotor repeatedly stops with the same end down, that end is too heavy. Cut 3 inches of magnet wire and wrap it on top of the coil near the end of the rotor which repeatedly stopped uppermost. Spin the rotor several more times, and add another piece of wire or remove some of the 3 inches until the rotor is balanced. A slight unbalance will not matter.

The Stator

Bend the stator base and the stator core to the shapes shown in Fig. 5-25. Cut two pieces of Scotch Tape $1\frac{1}{2}$ inches long and $\frac{1}{2}$ inch wide to tape the stator core to the stator base. One edge of each piece of tape *must* extend beyond the two mating parts of the core and base, as shown in the figure. Cut 10 more feet of magnet wire. Leaving 1 foot of wire free, start winding the stator coil. End up with at least 3 inches of wire free on the same side of the coil as the free end you started with. (You can see this in Fig. 5-26.) Cut a piece of Scotch Tape

2 inches long and $\frac{1}{2}$ inch wide, and wrap it around the coil.

Slip the assembled stator under the rotor as in Fig. 5-26, with the free ends of the coil toward the pointed end of the shaft. Line up the stator with the rotor in the direction that the shaft runs, and then center the stator on either side of the rotor. Hold the stator in place and spin the rotor to see that the rotor does not touch the stator at any point. If it touches on one side, shift the stator. If the rotor touches on both sides, bend the stator core open slightly. Then mount the stator on the wooden base with two upholsterer's nails through the holes in the stator base. After mounting, check once again to make sure that the rotor turns without touching the stator.

Drive two more upholsterer's nails part way into the

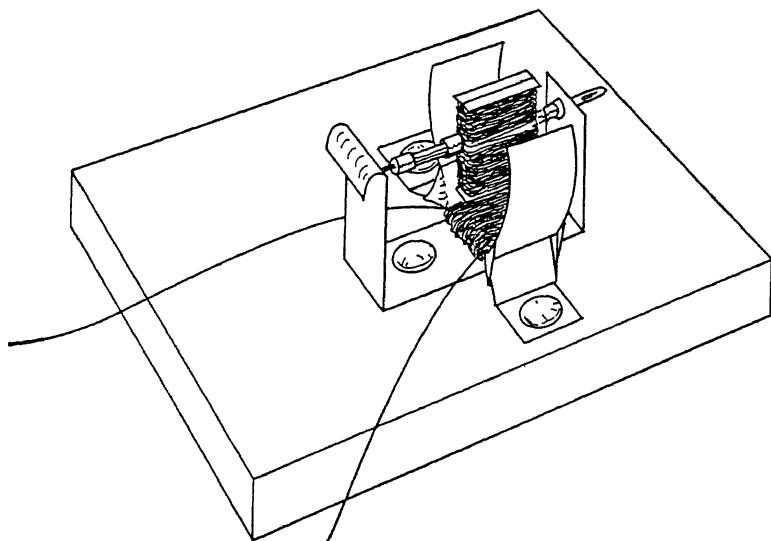
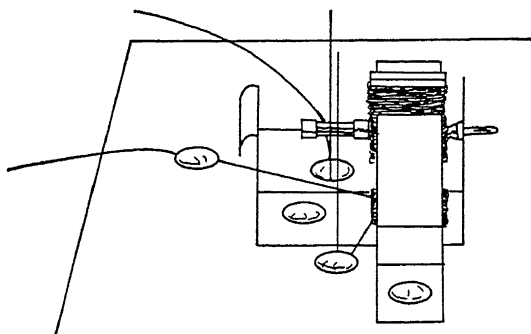


FIG. 5-26

FIG. 5-27



wooden base as in Fig. 5-27. Line them up with the enamel-free part of the wires on the commutator, and far enough out to the side so that the heads won't touch the bottom of the shaft support later when they are driven all the way in. Wrap one turn of the 3-inch end of the stator coil around one of the nails and drive the nail all the way in. Cut a piece of magnet wire 14 inches long, and 3 inches from one end take a turn around the other upholsterer's nail. Then drive that nail all the way in. Now bend the 3-inch ends up along the side of the commutator as shown and cut them off $\frac{1}{2}$ inch above the shaft. Bend them out away from the shaft and sandpaper the enamel insulation off the last inch. To do this, fold a small piece of sandpaper in half, sand side in, hold it around the wire, squeeze, and pull upward. Repeat the process until the wires are bright copper all around. These two cleaned wires are the brushes.

Draw the 1-foot end of the stator coil out so that it is clear of the shaft support and both brushes. With the wire held in position as in Fig. 5-27, place an upholsterer's nail touching it and near the motor. Drive the nail part way in, take a turn of wire around the nail, and drive it all the

way in. Sandpaper the enamel from the ends of the two long lead wires for connection to the battery.

Adjustments

You will have to make some final adjustments. Check the amount of end play in the shaft. Then adjust the brushes. This is a very delicate operation. First bend them over until they touch the commutator *but not each other* as in Fig. 5-28*A*. Then hold the rotor vertical and squeeze the brushes together around the shaft with your thumb and index finger (*B*). This will curve the brushes to the shape shown in *C*. As the rotor turns, the wires of the commutator will touch the brushes for a longer time than if they were straight. With the rotor vertical, each brush should touch one of the doubled commutator wires. If not (*D*), pull up on the end of the offending brush (*E*) to partly straighten the part of the brush between the commutator and the upholsterer's nail. Then press just heavily enough on the brush near the upholsterer's nail (*F*) to bring the brush in contact with the commutator.

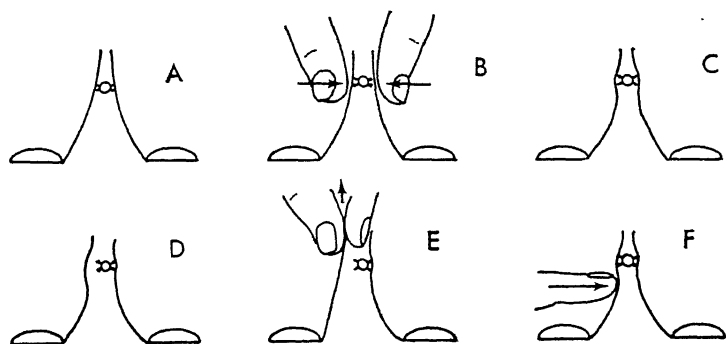


FIG. 5-28

MAKING ELECTRICITY WORK

Now the motor is ready to run as soon as you connect the two leads to the battery of your two-battery holder. Turn the rotor so that it is vertical. If the brushes are contacting the commutator properly, the rotor will make a fraction of a turn under magnetic power in one direction. Give it a flick with your finger in that direction and off it will go.

WHAT HAPPENS INSIDE THE MOTOR

Now that you have built a motor and understand the basic principles of its operation, you will be able to understand one of the main reasons why rotary motors can put magnetism to practical use. The reason is that it is easy to make the magnetism in them strong because the design

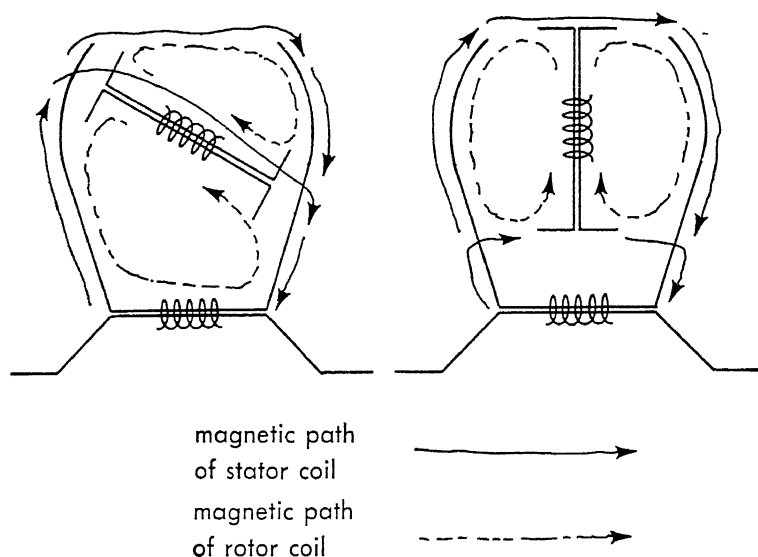


FIG. 5-29

provides magnetic circuits of low reluctance. The magnetic circuit of the stator of your motor runs, as in Fig. 5-29, through the coil, up the side of the stator, through a relatively *small* and relatively *constant* air gap to the rotor core, through another air gap, and down the other side of the stator. The magnetic circuit of the rotor runs through its coil and through either all or part of the stator core. More powerful motors are designed, as in Fig. 5-30, with *very* low and constant reluctance paths so that the magnetic force is stronger. The heavy rotor acts as a flywheel, so that, even when the brushes are switching, the motor provides a constant force to whatever it is driving.

The stator and rotor of a motor can have more than

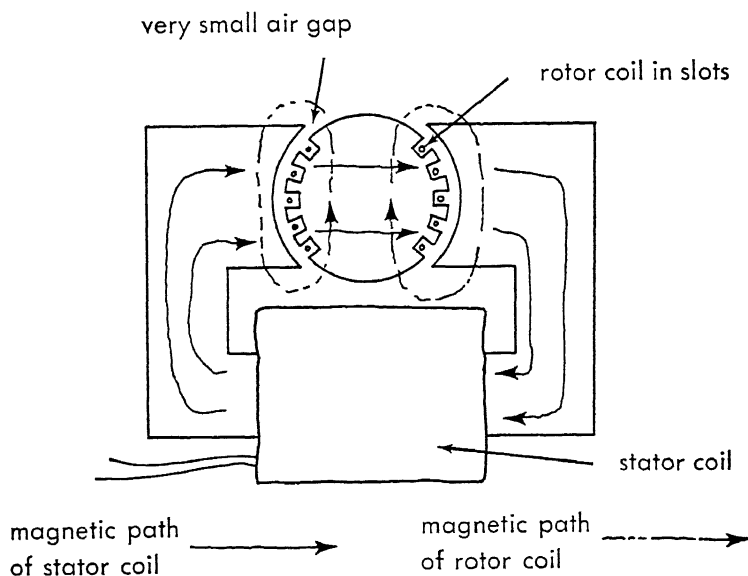


FIG. 5-30

MAKING ELECTRICITY WORK

two magnetic poles. Multipole motors give more power at slow speeds than 2-pole motors. A simplified sketch of a 4-pole motor is shown in Fig. 5-31. You can see how alternate north and south poles are formed by the four coils. Other motors have 6, 8, 10, or 12 poles.

Speed Regulation

Perhaps you may be wondering what regulates the speed of the motor and why the motor doesn't keep going faster and faster until it flies apart. It probably seems obvious (and it is true) that bearing friction and air resistance get stronger as the speed increases. These help to control the

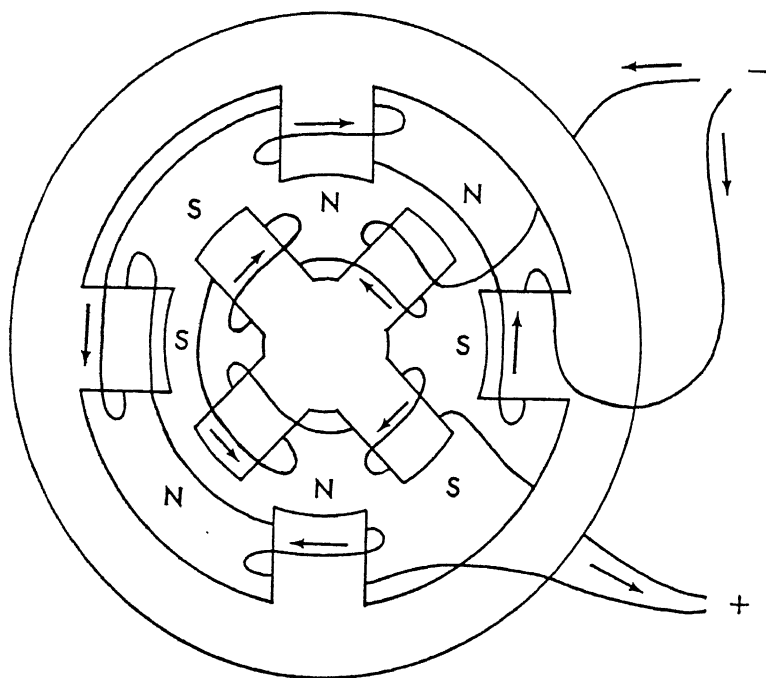


FIG. 5-31

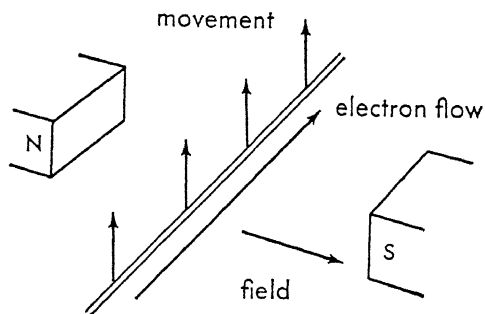


FIG. 5-32

speed. And of course if the motor is driving something, this load keeps the speed down. But there is another important reason why the motor reaches and does not exceed a certain constant speed. The reason is that the motor is a *generator* at the same time that it is a motor. The voltage that it generates partly counteracts the voltage from the battery, and the faster the motor goes, the more counter-voltage it generates.

How does the motor generate this countervoltage? To understand how, we have to look from another point of view at the way motion is produced in a motor.

In Fig. 5-14 the rotor coil produces a north pole at the top, and the stator coil produces a north pole at the left. Since these poles repel, the rotor turns clockwise. As it does so, the wire on the left-hand side of the rotor coil moves up. *If there were no rotor coil, but just one wire carrying current between the ends of the stator, as in Fig. 5-32, it would move up too.* If it were carrying current in the other direction, it would move down. So without considering that the rotor coil forms a magnet, but by simply recalling that a wire carrying current across a

MAKING ELECTRICITY WORK

magnetic field will move, we have now explained, in slightly different terms, the motor action in Fig. 5-14.

You can demonstrate, as in Fig. 5-33, that this really works. Cut a 2-foot piece of magnet wire and mount it as shown. Sandpaper the ends of the wire, and clip one end as shown to the negative (base) terminal of your two-battery holder. Place your alnico magnet $\frac{1}{4}$ inch under the wire with the poles arranged as shown. When you touch the other end of the wire to the positive terminal (cap) of the battery holder, the wire will snap down

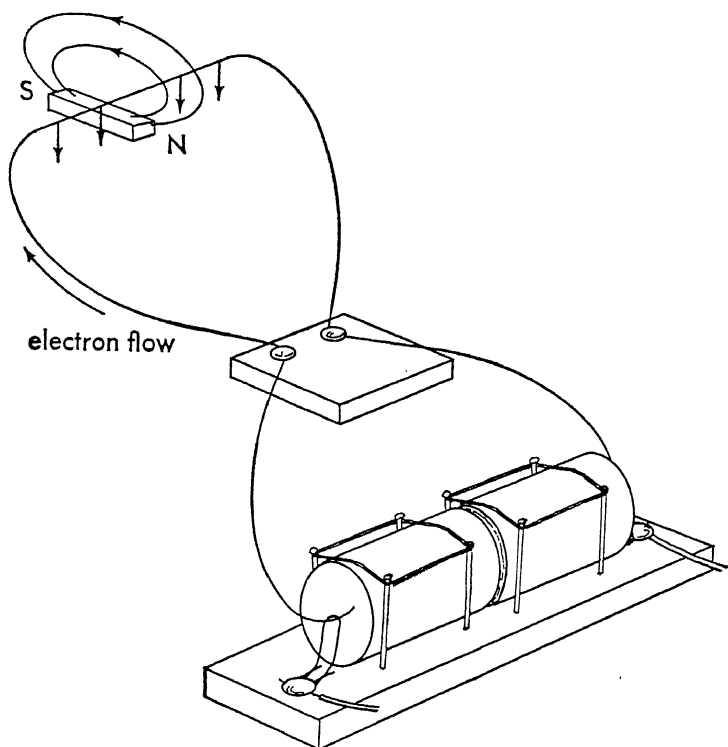


FIG. 5-33

against the magnet. Repeat the process with the poles of the magnet and the terminals of the battery reversed. Again the wire will snap down. With *only* the poles or *only* the terminals reversed, the wire will jump up away from the magnet and vibrate against its own springiness. Part of the field pattern of the magnet has been shown in Fig. 5-33. The wire, and therefore the direction of electron flow, is arranged perpendicular to the direction of the magnetic field. The force exerted on the wire, and therefore its movement, is perpendicular to both the field and the direction of electron flow as shown. The direction of the field is from the north pole to the south pole (the direction that the north pole of a compass will point; the direction of the arrows in the field-pattern illustrations).

You can see that it is important in motor action for the wire to be carrying current *across* the magnetic field. If you turn your alnico magnet so that its poles—and therefore its magnetic field—are lined up *in the same direction* as the wire, only a slight motion will result when you make current flow. This slight movement results because the wire and field are not perfectly parallel. If the wire is at an acute angle to the field there will be some force, but less than when they are at right angles. Try the experiment with the magnet at several angles to the wire. The stronger the magnetic field at right angles to the wire, or for a magnetic field of given strength the more nearly it is at right angles to the wire, the stronger will be the force tending to move the wire. And the longer the piece of wire that is in the field, the stronger the force will be,

which is why we wound many turns on the rotor.

From this new point of view on how a motor is made to turn over, we can examine how it also acts as a generator. If a wire carrying current across a magnetic field will produce a force to make the wire move, can it be that the movement of a wire across a magnetic field will produce a voltage to make a current flow in the wire? The answer is yes.

The development of a force tending to move a wire which is carrying current across a magnetic field is called *motor action*. The development of a voltage tending to produce a current in a wire which is being moved across a magnetic field is called *generator action*. Motor action and generator action are closely related. If a wire carries current across a magnetic field, a force will be exerted on the wire tending, as we have seen, to move the wire (motor action). This movement, in turn, makes the wire generate a voltage which will oppose the current. If the wire is prevented from moving—as if, for example, you were to hold back the rotor of your motor—no voltage opposing the current is produced. The supplied current will be limited only by the electrical resistance of the wire. The faster the wire moves under the force of motor action, the more opposing voltage will be generated. But a motor can never turn fast enough solely by reason of motor action to generate enough countervoltage to stop the flow of supplied current altogether.

Now you can see that a motor will settle down to a speed that will produce an opposing voltage, which, in turn, will allow a current to flow that is just sufficient

to supply the energy used up by friction, by air resistance, by heat loss due to the electrical resistance of the motor wires, and by whatever the motor is driving.

GENERATORS

And now you can see how a generator works. Suppose, instead of the motor's driving something, it was being driven *by* something—say a gasoline or steam engine. The engine could make the motor speed great enough so that the generated voltage would stop the current from the battery. Trace the circuit in Fig. 5-15 and you will see that it would not stop the current to the stator coil which is producing the magnetism. Now imagine (Fig. 5-34)

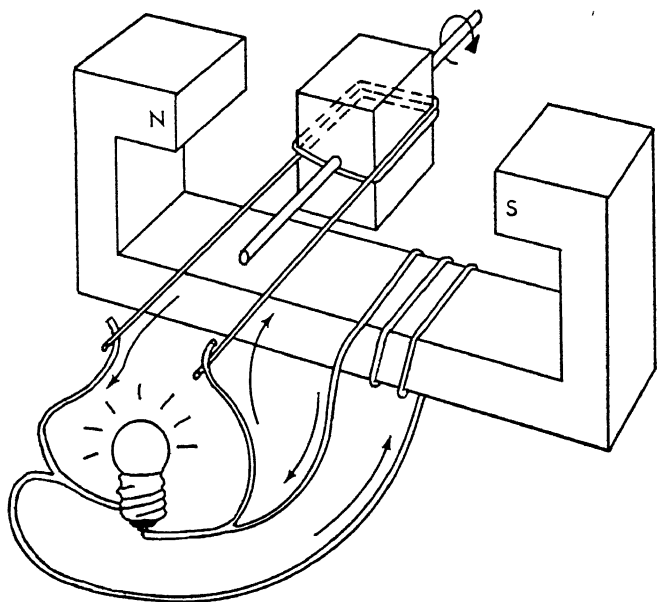


FIG. 5-34

taking away the battery and replacing it with a light bulb. With no current to oppose, the generated voltage produces a current in the opposite direction. Notice that it continues to produce a current in the same direction through the stator coil, which will therefore produce the same magnetic field as when it was receiving current from the battery. You might think that the generator would never start producing voltage, because when we began to turn it with the engine there would be no current for the stator coil. But the stator core has some permanent magnetism from the last time it was used, and this is enough to get things started. New generators are given some permanent magnetism by connecting a battery to the stator coil for a few minutes. (Some small generators—and some small motors for that matter—are built with permanent magnets in place of the stator coil.)

In a generator, motor action—the force on a wire carrying current in a magnetic field—opposes the generator action. Generator action causes a current to flow through a wire passing across a magnetic field. But this generated current produces force which works toward preventing the generator from turning. If it did actually prevent the generator from turning, no current would be generated and there would be no motor action to oppose the engine. The force produced by the motor action depends on the current flowing through the generator. If the generator were not connected to a load—lights or something else which draws current—it would still generate voltage, but no current would flow, and therefore there would be no motor action to oppose the engine. The engine would have

to work only hard enough to supply energy to overcome friction in the generator and to provide power for the stator coil. The operator would have to cut back the throttle on the engine to keep the speed from increasing. As more and more lights or other loads were switched on, allowing the generator voltage to drive current through them, motor action would begin to oppose the engine and the operator would have to advance the throttle to make the engine produce more power or the generator would slow down. In big generators there are automatic controls to operate the engine throttle. The important thing to see is that the energy used by the load comes from the engine driving the generator, and an increase in energy output requires an increase in energy input.

The mechanical construction of your motor will not permit you to drive it with an engine and thus use it as a generator. You can't turn it fast enough by hand to light a bulb, and it would take a sensitive voltmeter to measure its output. But you can easily produce generator action with your relay, as we shall now see.

INDUCTION

Induction is the term used to describe the action that takes place when a current or voltage causes—or induces—another current to flow or another voltage to exist. The action in a motor is a special case of induction—current in the rotor produces motion, which, in turn, produces a counteracting voltage.

Your relay employs a coil of wire with a current flowing in it. When the current is flowing, there is a magnetic

field through and around the coil. Fig. 5-35 shows how the field forms when you connect a battery to a coil and current starts to flow. The core in Fig. 5-35 is a simpler one than your relay coil, to make it easier to see the action. A motion picture would show the formation of the field better. The lines of magnetic force in the successive views move out through the coil from the core like waves from a pebble thrown in still water (except that they move out in all directions and not only in one plane). In a fraction of a second the field and current both build up to maximum strengths, the field becoming stationary and the current constant.

Why doesn't the current reach its maximum value instantly instead of taking a fraction of a second? Generator action is the reason. The magnetic field moves across the wires of the coil as it moves out from the core. Since all motion is relative, a magnetic field moving across a wire has the same effect as a wire moving across a magnetic field. The moving field induces in the wire of the coil a voltage which opposes the current that is causing the field to move. At the other side of the coil, where the field is moving in the opposite direction, the current is flowing in the opposite direction; hence the induced voltage opposes the current there too. The induced voltage can't stop the current, because it is the current which is causing the moving field to form and the moving field is inducing the voltage. If there were no iron core in the coil, the magnetic field would be weak and would induce very little opposing voltage; hence the current would build up rapidly—but not in proportion to the weakness of the field. The weak-

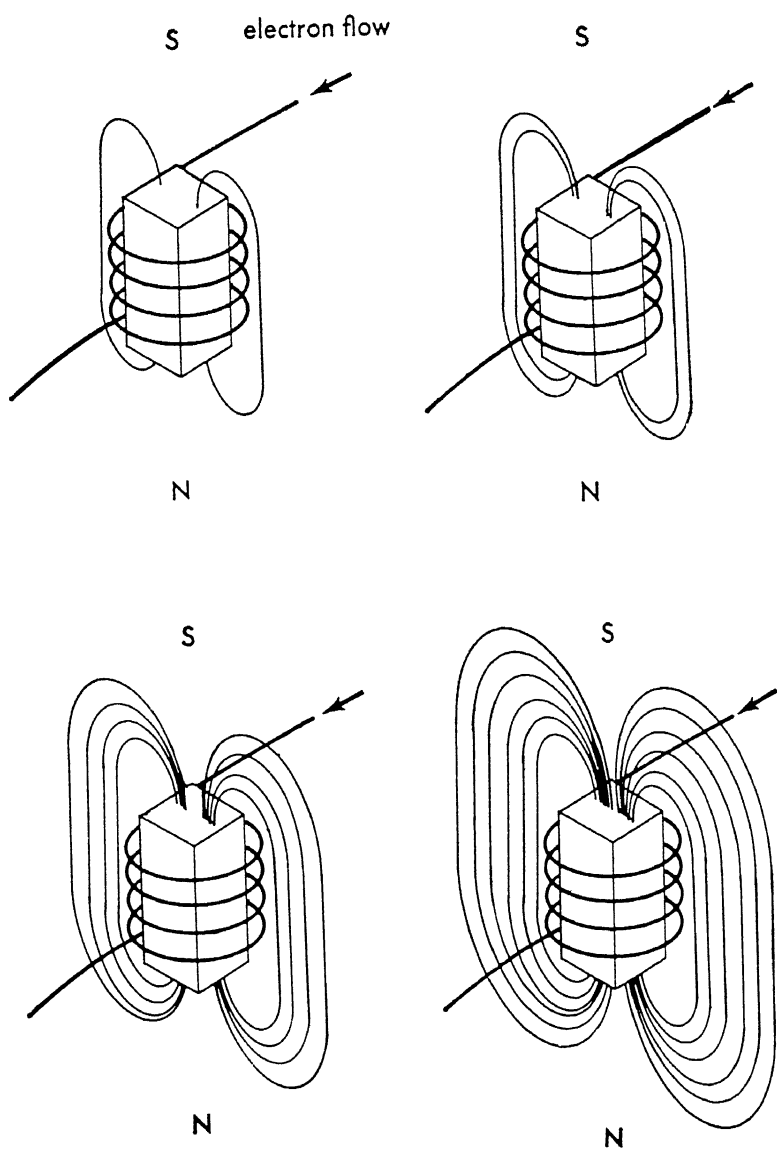


FIG. 5-35

ness of the field allows the current to build up rapidly, which means that the field moves fast in forming to its full value. A fast-moving field generates more voltage than a slow-moving field of the same strength cutting across a wire of the same length. You can see that there is a nice balance among coil resistance (which determines the final current for a given applied voltage), magnetic reluctance (which determines how much magnetic field strength the ampere-turns of the coil will produce), and the induced voltage (which determines the speed with which the current attains its final value).

The Field Reversed

Now let us see what happens when you open the circuit of the coil after the steady current has been established. The moment you open the switch, the current stops because there is no longer a circuit. The field, having no current to maintain it, immediately begins to collapse in the reverse of the way it formed in Fig. 5-35. Now it moves across the wires in the opposite direction from that when it formed, and it therefore induces a voltage of opposite polarity to the voltage it induced when it formed. This new voltage works toward producing a current in the same direction as the current which was flowing just before the switch was opened, but it cannot maintain the current because there is no circuit—since the switch is open—for the current to flow through. If current could flow—as it could, for example, if you had short-circuited the battery to stop the original current instead of opening the switch—the induced current would tend to maintain the

field, and, although it could not completely maintain it, the collapse of the field would be slowed down to approximately the speed at which it formed originally. But since you did open the switch and current cannot flow, the field collapses with great rapidity. You will remember that the number of volts induced when a wire and a magnetic field move relative to each other is determined in part by the speed of movement. As you open the switch in the circuit of your relay coil, the speed with which the collapsing field moves across the wire is far greater than the speed with which it moved while forming. As a result the induced voltage is very much higher than the induced voltage which opposed the current as the field formed.

High-voltage Demonstration

You can see and feel the effects of this high voltage that is induced when your relay coil circuit is opened. Connect your relay and two-battery holder as in Fig. 5-36. Touch

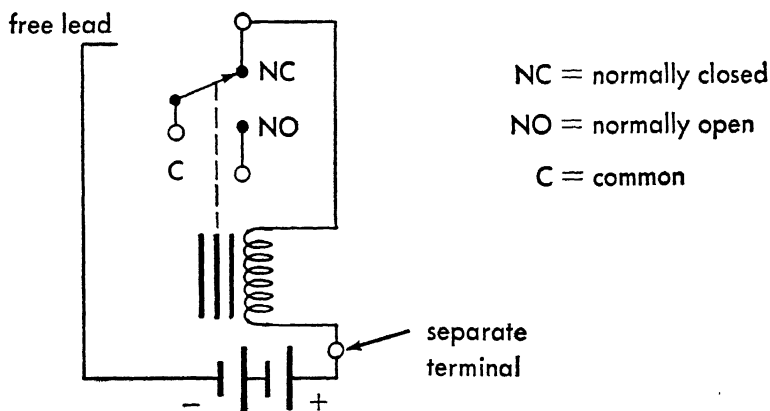


FIG. 5-36

the free lead of the two-battery holder to the *normally closed* contact terminal. Make the touch squarely and firmly without making and then breaking the circuit. Now remove the lead and you will see a bright spark as the lead separates from the terminal. Of course a spark is a current of electricity flowing through the air. The spark doesn't start until after the circuit has actually been broken and the current has stopped. The voltage induced by the rapidly collapsing field becomes so high so quickly that it forces current to jump the gap between the lead and the terminal. The spark lasts for only an instant, because as soon as current flows, the collapse of the field is greatly slowed down and the induced voltage falls to a low value, insufficient to maintain the spark. And of course the distance between the lead and the terminal keeps increasing as you move them apart. The voltage required to make a spark is greater the farther a spark has to jump.

How high is the voltage that is induced as you open the coil circuit of your relay? Try another test. Press the index finger of your left hand firmly against the separate terminal (see Fig. 5-37) to which one end of the coil is connected, and the thumb of your left hand firmly against the normally closed contact terminal to which the other end of the coil is connected. Now touch the free battery lead firmly and squarely to the normally closed contact terminal. Remove the lead and you should feel a distinct shock. If not, wet the skin between your thumb and index finger to make it a better conductor. The shock is harmless because you draw very little current. Even the slight current you do draw is enough to reduce the induced voltage

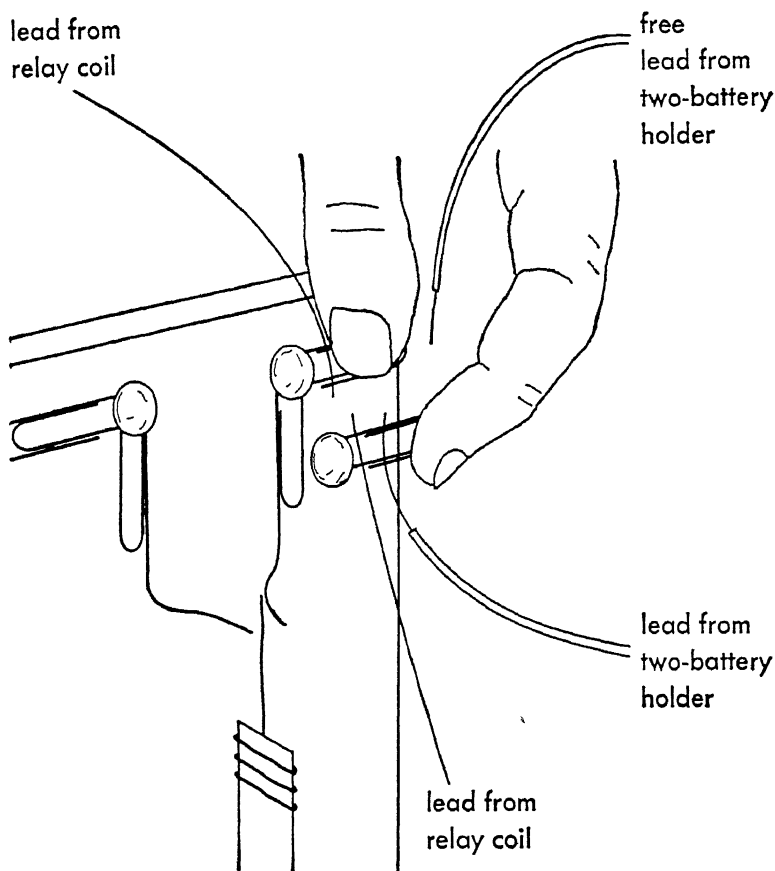


FIG. 5-37

—by slowing the collapse of the field—to less than enough to maintain the sensation of shock. It is never a good idea to shock people by surprise. They may jump or be frightened and get hurt even though the current is harmless. So *don't shock friends*.

Now let us get some idea of how many volts are induced. We know that we cannot get a shock from the

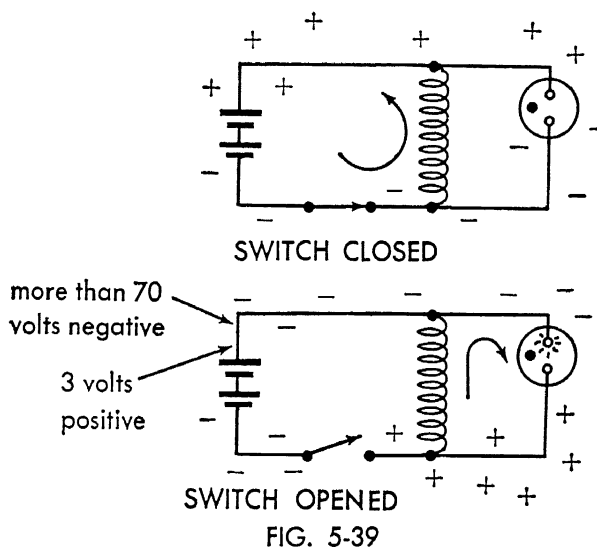
3 volts of our two-battery holder. It takes something like 35 volts to produce the sensation of shock. The collapse of the field as the current stopped produced at least 35 volts—and a lot more, as we shall see—even though the original current was produced by only 3 volts. We can measure the voltage somewhat more accurately by means of a neon glow bulb.

The Neon Glow Bulb

A neon glow bulb can be used as a crude voltmeter because it requires about 70 volts to light. It consists of two wires leading into a glass bulb containing neon gas (see Fig. 3-2) at low pressure. Connect it as in Fig. 5-38 to the points at which you held your thumb and index finger when you shocked yourself. Touch the free battery lead briefly to the normally closed contact terminal; as you remove it, one wire inside the neon bulb will flash. This shows that at least 70 volts is induced.

Here is how the neon glow bulb works. With about 70 volts between the two wires, the positive wire pulls an electron off each of many neon atoms. The atoms become positively charged neon ions and are repelled by the positive wire and attracted by the negative wire. When it hits the negative wire, each ion gets back an electron. When the electron moves into its orbit in the neon atom, the atom gives off light. Once current has begun to flow through the neon bulb, about 55 volts will maintain conduction.

Because they use very little current, neon bulbs are used as pilot lights where it is important to save power. They



ceive electrons. You will notice when you light the bulb that this is the wire connected not to the negative side (base terminal) of the battery, but to the positive side. Fig. 5-39 shows why. Only the coil of the relay is shown in Fig. 5-39, and the wire you touched is represented as a switch. The unfamiliar symbol is the neon bulb. (In any symbol of a bulb a solid black dot not connected to anything means that the bulb is gas-filled.) The first schematic shows the electron flow and polarity before you opened the switch. The second shows the conditions after the switch is opened. Note that the direction of current is the same through the coil in both cases but that the polarity of the voltage across the neon bulb has reversed.

Now touch the free battery lead to the common terminal of the relay. The relay will act as a buzzer, and each time the contacts open the neon bulb will light. Your eye gives

you the impression that the bulb is lighted continuously because your eye cannot respond to such very rapid changes.

CAPACITORS

There is another very important electronic component called a *capacitor*, or, less commonly today, a condenser. A capacitor in a circuit acts like a reservoir in a water supply system which in the rainy season collects excess rainfall and maintains the supply of water in the dry season. A capacitor can be charged with electrons and then act as a battery.

A capacitor consists of two sheets of metal or other conducting material separated by a very thin piece of insulating material. If two sheets of metal are connected to the terminals of a battery, some electrons will move out into the sheet connected to the negative terminal and some electrons will be removed from the sheet connected to the positive terminal. But if the two sheets are very close together, the electrons entering the negative sheet will repel and drive out electrons from the positive sheet. The positive metal ions formed in the positive sheet by removal of electrons will attract electrons into the negative sheet. The bigger the sheets and the closer they are together, the more electrons will crowd into the negative sheet.

You can make a capacitor and use it in one of its common applications—the suppression of sparks in relay contacts. Cut two sheets of aluminum foil and two sheets of Saran Wrap each 12 by 16 inches. Lay them together as

in Fig. 5-40 *A* and *B* and smooth the air out from between them. Then roll them up as in *C* and fold the roll as in *D*. Tape the capacitor together with Scotch Tape as in *E*.

Spark Suppression

You may have noticed that when your buzzer is operating, the contacts spark as they are opened. You now know that this is the result of the induced voltage as the field collapses around the coil. If a capacitor is connected in parallel with the contacts, the collapsing field will be able to produce some flow of electrons into the capacitor and the collapse will be slower. The induced voltage will then be lower and sparking will be reduced.

Connect one foil lead of your capacitor to the common contact terminal of your buzzer without the neon bulb connected. Start the buzzer and observe the contact sparks in a very dimly lit room. Touch the second foil lead of the capacitor to the normally closed contact terminal. You will notice that the sparking is reduced when the capacitor is connected. Repeat the process with the neon bulb connected as in Fig. 5-38. When the capacitor is connected, the neon bulb will not light.

The Capacitor and the Neon Bulb

Connect your neon bulb and your capacitor in *series* in place of the neon bulb in Fig. 5-38. The lead of the neon bulb and the foil lead of the capacitor can be joined by folding and squeezing the foil around the wire. Touch the free battery lead to the normally closed contact ter-

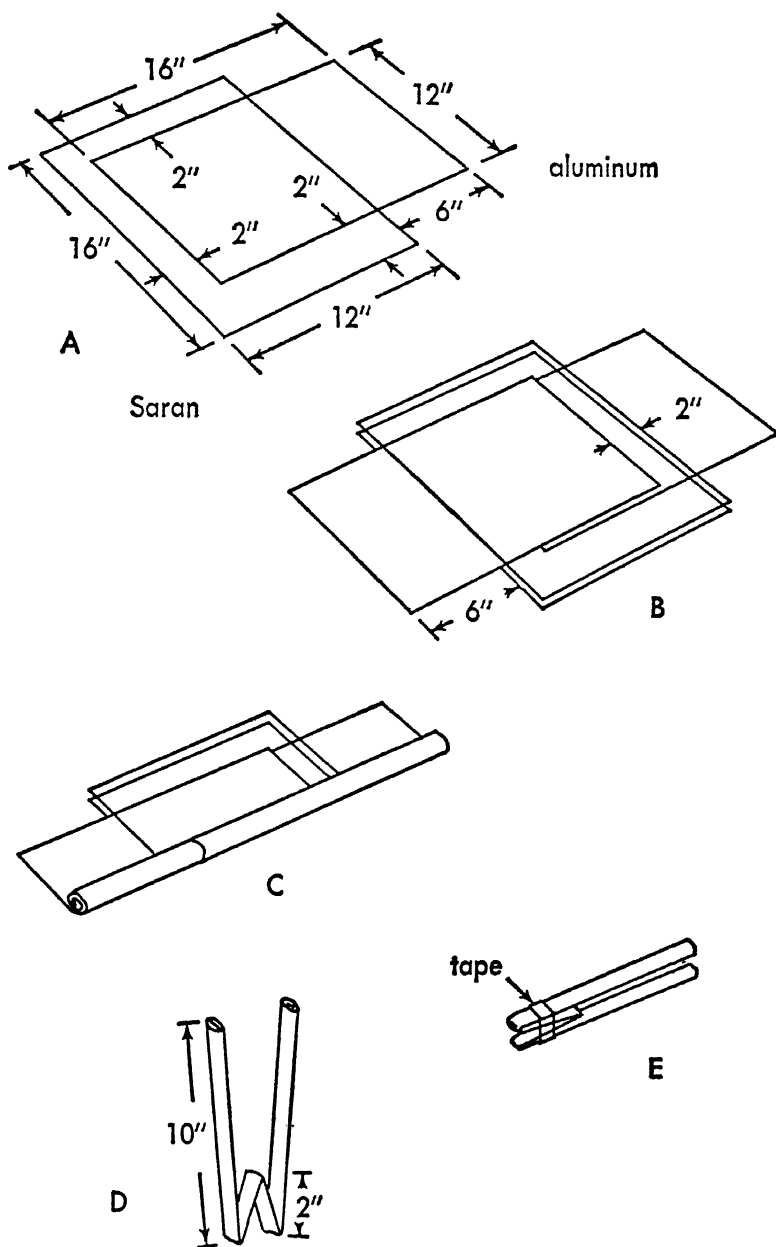


FIG. 5-40

MAKING ELECTRICITY WORK

minal and remove it. The neon bulb will light, but with a difference. Now the flash of light is around *both* wires inside the bulb.

Fig. 5-41 shows why. The new symbol in the schematic is the capacitor symbol. When the contacts open, the collapsing field induces its more than 70 volts. One wire of the neon bulb flashes and a great surge of electrons flows through the bulb into the capacitor, charging it to the more than 70 volts. The field finishes collapsing and now the top (in Fig. 5-41) sheet or plate of the capacitor is full

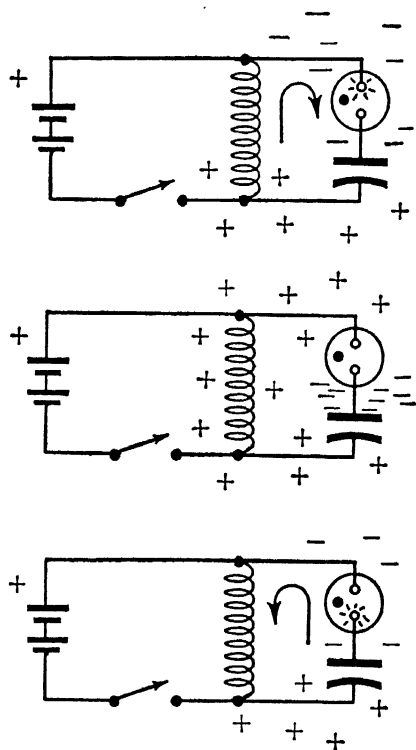


FIG. 5-41

of electrons. The electrons surge back through the neon bulb in the *opposite direction* and produce a new flash of light on the other wire.

You can see this operate in a more spectacular manner if you connect the free battery lead to the common-contact terminal of the buzzer. The process will be repeated each time the contacts open, and both wires in the bulb will appear to remain lit.

ALTERNATING CURRENT, OR A.C.

Up to now we have been working with what is called *direct current*, or D.C. Our source—a battery or a generator—has produced voltage which is positive at one terminal and negative at the other, and electrons have always come out of the negative terminal and returned to the positive terminal. As you know, there is another important kind of current called *alternating current*, or A.C. In A.C. the electrons surge through the circuit in one direction, come to a stop, and then surge through the circuit in the other direction, repeating this reversing process many times each second. You have seen something like A.C. when the induced voltage in your relay coil drove current through the neon bulb into the capacitor, where the current came to a complete stop and then surged back through the neon bulb.

Alternating current, although it cannot be used in all applications of electricity, has many advantages over direct current and can be converted into direct current when that is needed. One important advantage of A.C. over D.C. is that motors designed to operate on A.C. can be built to

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operate for years without requiring any repairs. When you know more about A.C. and how it works, you will see why.

By far the most important advantage of A.C. over D.C. is that the voltage at which it is generated can be changed to a higher or a lower voltage very easily with very little loss of power by means of an electrical component called a *transformer*. When we need several different voltages—6 volts to work a door bell, 110 volts for lights and appliances, and 220 volts for the electric stove—we don't need several power lines from the power company; we can use one power line and a variety of transformers. (We shall build a transformer later in this chapter.) This is an important advantage because power lines are expensive compared to transformers. But there is another reason why being able to change voltage reduces the cost of distributing electric power. You will understand this, too, when you know more about A.C.

The best way to understand A.C. is to look at its graph, which is a picture of the way the voltage changes as time progresses. First let's look at two graphs of D.C. voltages to get the idea of how a graph works. Fig. 5-42 is a graph of the voltage of a battery supplying current to a bulb over a period of 4 hours. The *voltage curve* is the heavy black line running across the figure. The amount of voltage is indicated by the height of the voltage curve above the horizontal line at the bottom of the graph. Along the left-hand edge of the graph is a scale against which you can read the amount of voltage. Since voltage drops as

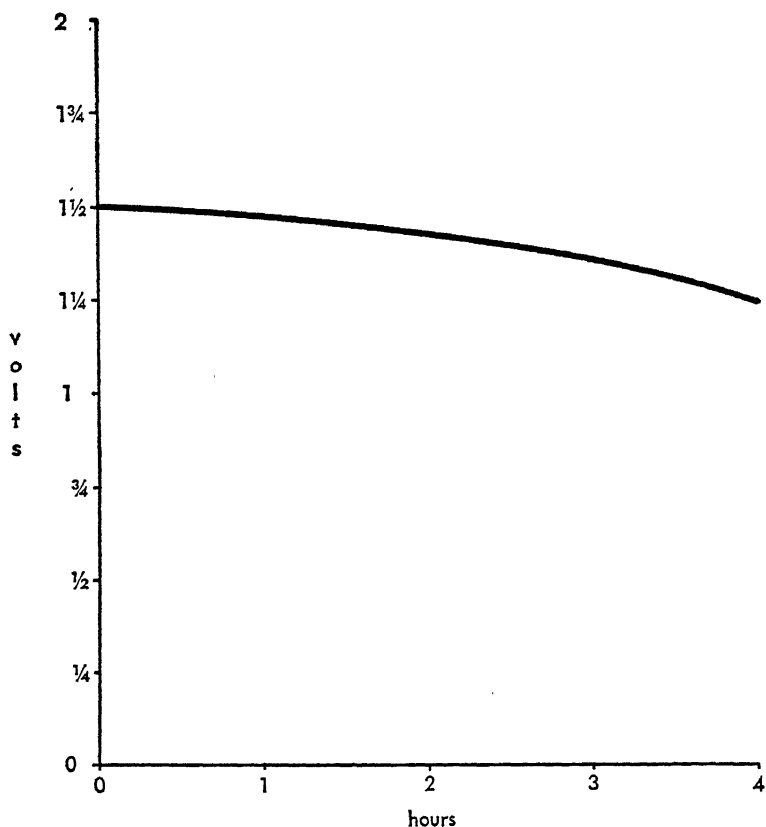


FIG. 5-42

time progresses, the voltage curve is not always the same distance above the zero-voltage line. You can see that when the battery started supplying current, it gave $1\frac{1}{2}$ volts because the curve starts at zero time and at the $1\frac{1}{2}$ -volt mark. At the end of 4 hours the voltage was down to $1\frac{1}{4}$ volts. At 1, 2, and 3 hours, and any time in between, the voltage as shown by the curve was between $1\frac{1}{2}$ and $1\frac{1}{4}$ volts.

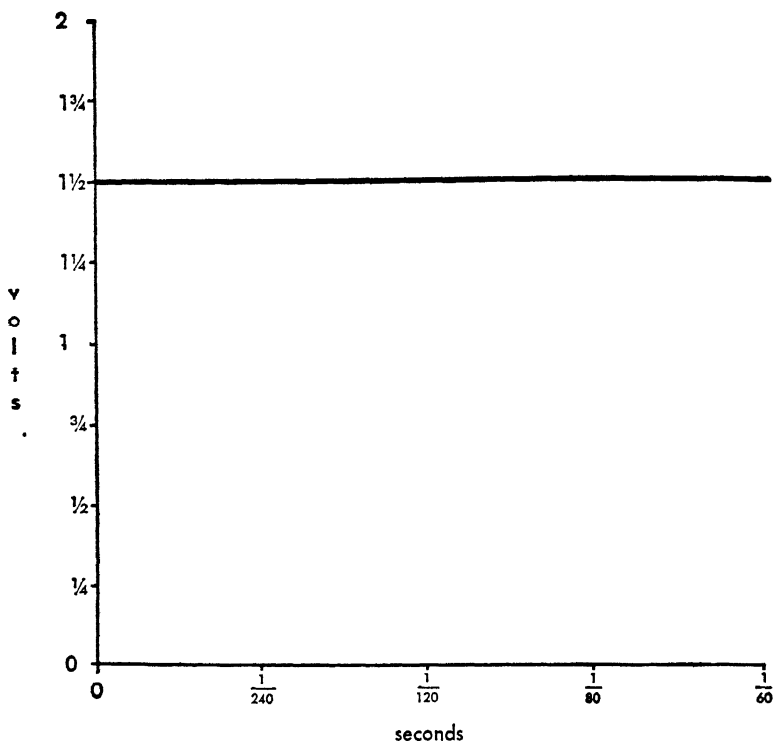


FIG. 5-43

Fig. 5-43 shows the voltage of the same battery during the first $\frac{1}{60}$ second of operation. The “curve” is a straight line because the voltage changed only imperceptibly during the first $\frac{1}{60}$ second.

Now look at Fig. 5-44. This is a graph of the voltage of a 110-volt A.C. power line during $\frac{1}{60}$ second. The voltage curve drops *below* the zero-voltage line in this graph because when the direction of electron flow reverses, the polarity of the voltage reverses too. Positive voltage is shown above the zero-voltage line and negative voltage below. Here positive and negative mean the polarity of

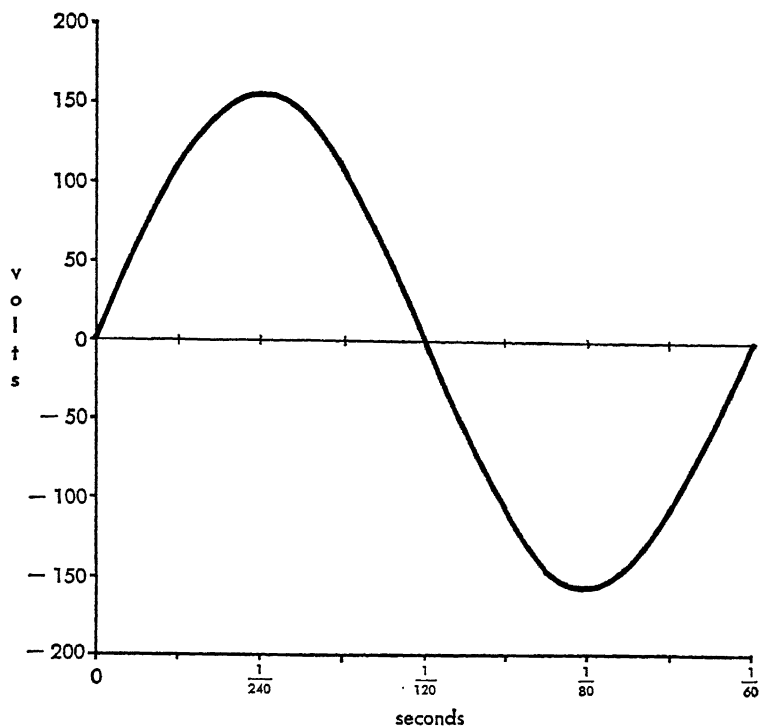


FIG. 5-44

one arbitrarily selected wire with respect to the other. (You will remember that in a battery both electrodes have excess electrons, the electrode with the *most* excess electrons being the negative electrode.) In drawing the graph, zero time is taken as the time when the electrons are standing still. After $\frac{1}{240}$ second the electron flow and the voltage have reached a maximum, and after that they begin to decrease. By the time $\frac{1}{120}$ second has elapsed, the electrons are again standing still and the voltage is zero, after which they begin to move in the opposite direction. After $\frac{1}{80}$ second, flow is at a maximum again and the voltage has

reached a maximum negative value, and by $\frac{1}{60}$ second it is again at zero. In the next $\frac{1}{60}$ second the same pattern repeats again (but that fact isn't shown by the graph).

When a complete cycle of change—zero flow to maximum, back to zero, to maximum in the other direction, and again back to zero—is $\frac{1}{60}$ second, the current is said to be 60-cycle current. The number of cycles per second is also called the *frequency*. Your house current probably has a frequency of 60 cycles. Frequencies of 50 and even 25 cycles are sometimes used in supplying electric power. On 60 cycles the filament of a light bulb doesn't cool off very much during the two times in each cycle that the current is near zero; hence the light output is constant. There is some slight flicker at 50 cycles, and a noticeable flicker at 25 cycles.

You may wonder why the maximum voltage in Fig. 5-44 is 156 volts (positive and negative) and not 110. Since an A.C. voltage is always changing, the voltage by which it is designated—for example, 110, 220, 11,000—is always what is known as the *effective* voltage. An A.C. voltage whose maximum or peak voltage is 156 has an effective voltage of 110 because it will produce the same heating effect in a resistor as will 110 volts D.C. The curve in Fig. 5-44 is a picture of what is called the *wave shape* of A.C. A.C. doesn't always have such a smooth wave shape, but in supplying power every effort is made to produce that shape.

A.C. GENERATORS

Fig. 5-45 is a simplified picture of an A.C. generator. You will notice that it looks almost exactly the same as

200

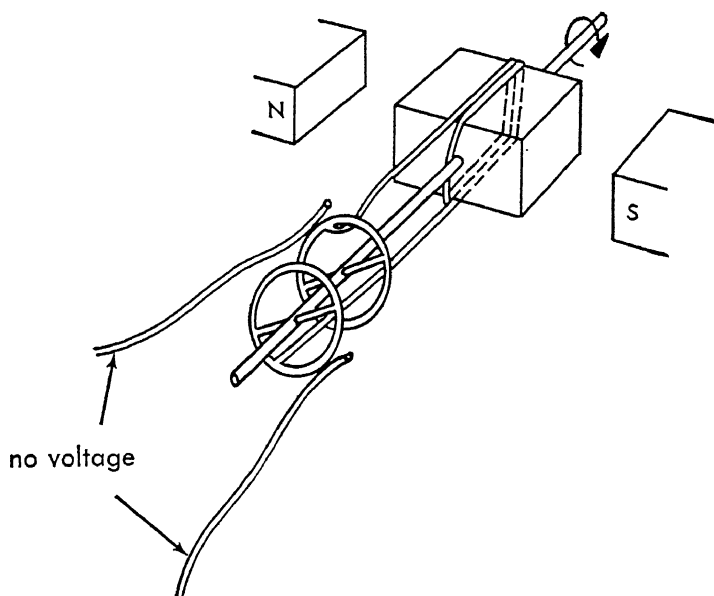
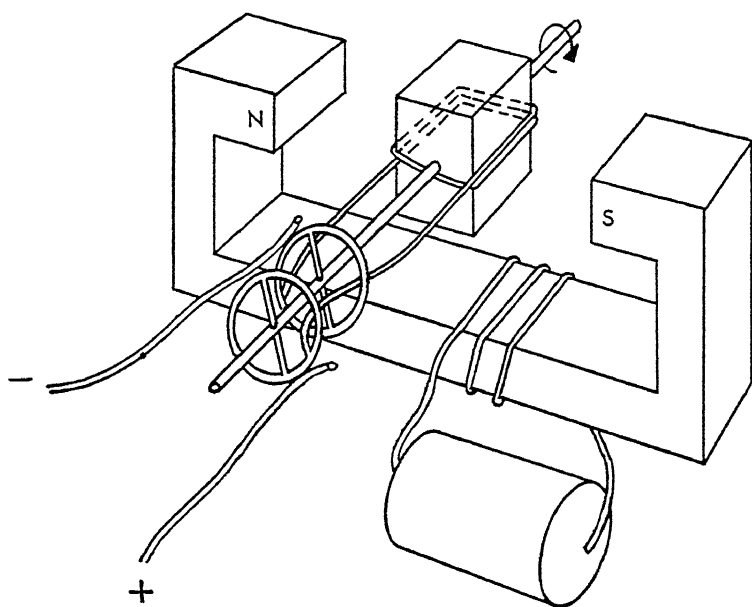


FIG. 5-45

the motor in Fig. 5-15 except for the very important fact that there is no commutator. Instead, the ends of the rotor coil are brought to what are called slip rings, from which brushes lead away the electricity. As the shaft of the rotor is turned at high speed, the wires cut through the magnetic field of the stator. When the wires are in the position shown in the lower view, they are moving in the direction of the magnetic field and no voltage is induced in them. When they get to the position shown in the upper view, they are cutting across the field at right angles and the maximum voltage is induced in them. In between, the wires move at a constantly increasing angle to the direction of the magnetic field, and the induced voltage increases to the maximum. So far this action is represented by the first quarter of the curve in Fig. 5-46. During the next quarter turn the angle changes from a right angle to zero, and the voltage drops from maximum to zero. During the next half turn the wires repeat the same action, but this time they are crossing the field in the opposite direction and voltage of opposite polarity is induced. Since there is no commutator to re-reverse the voltage, A.C. is produced at the terminals of the generator.

The speed with which the shaft is driven determines the frequency. If the shaft is made to rotate 60 times a second, the frequency produced is 60 cycles. But 60 revolutions per second is 3600 revolutions per minute, which is very fast for even a medium-size generator. Generators, like motors, can have more than one pair of poles. Big ones usually have many pairs. A 12-pole generator—one with 6 north poles and 6 south poles—has to be driven at only

10 revolutions a second to produce 60 cycles, because a cycle is generated each time a rotor wire passes a single pair of poles.

Because there is no direct current produced to supply the requirement of the stator coil, a separate source, like the battery in Fig. 5-45, must be provided. Since the D.C. required by the stator is much less than the A.C. produced by the generator, the design of big generators is turned inside out, with the coils to produce the magnetic field on the rotor and the wires in which the alternating current is induced distributed around the stator. In such a design the brushes and slip rings are required to carry only the small current for the magnetic field instead of the heavy generated current. The D.C. for the stator is often supplied by a small generator on the same shaft.

TRANSFORMERS

In order to get the many advantages of being able to change the voltage of A.C. easily and economically, we need a device called a transformer. We can readily understand how a transformer works if we first examine our relay once again. There is an important similarity between A.C. and the current in your relay when you operate it as a buzzer: both currents fluctuate rapidly. When you turn on the current to your relay and the magnetic field forms, it cuts through the wires of the coil and induces a voltage. When you open the circuit, the field collapses and again cuts through the wires and induces a voltage. If there were a second coil (with its leads not connected to anything) around the first, the magnetic field would induce a

voltage in it, too. If the second coil were connected in a circuit, the coil would act as a voltage source to supply current to this second circuit.

Try it with your relay. Pry the two wooden parts apart and remove the vertical one. Bend the moving arm out of the way so that you can wind a second coil over the first. Tag the two leads of the relay coil with tape so you won't get them mixed up with the leads of the new coil. Cut a piece of magnet wire 80 feet long and wind it around the first coil, leaving 1-foot leads. The direction of winding doesn't matter since we are dealing with A.C. This time you should get about 500 turns. (You won't get so many turns per foot because, being on top of the first coil, each turn uses up more wire.) Wind as much wire as you can into the spaces at the ends of the first coil and you will get more turns. Tape the coil to keep it from unwinding. Sandpaper the leads of the new coil. Reassemble your relay and readjust the contacts as before. Connect it as in Fig. 5-36, leaving the new coil disconnected. Try the relay to make sure it still operates as a buzzer.

Connect the neon bulb and capacitor in series as before, see that the bulb lights, and remove them. Now connect the *new* coil to the neon bulb. (Twisting the coil leads around the bulb leads makes an adequate connection.) Operate the relay as a buzzer and one wire inside the neon bulb will light. With the neon bulb and capacitor in series, both wires will light. Note that there is no electrical connection—only a magnetic one—between the battery and the neon bulb. Each turn of a coil contributes its bit to the voltage of the coil. The coils act as though they were tiny batteries or generators in series.

You had to wind about 500 turns in the second coil to get as much voltage as was induced in the 400 turns of the first coil. Since the second coil is outside the first, not all the magnetic field cuts the second coil. Commercial transformers are wound so that almost all of the field cuts through both windings, and if both windings have the same number of turns the same voltage is induced in the second coil as is applied to the first. If A.C. of a given voltage is connected to one of these coils, A.C. of the same voltage is induced in the other coil. If the second coil (called the *secondary*) has twice as many turns as the first coil (called the *primary*) the A.C. voltage induced in the secondary will be within a fraction of a percent of twice the voltage applied to the primary. If the secondary has half as many turns as the primary, the induced voltage will be half the applied voltage. And this, in brief, is how transformers change the voltage of A.C.

Another very important fact about a transformer—which you must understand before we can see how they save millions of dollars every year—is that the *power* supplied to the primary is equal (except for very small losses) to the *power* supplied by the secondary coil to the secondary circuit. If the secondary of a transformer is left unconnected, the current flowing in the primary will be very small—just enough to magnetize the core. If the turns ratio is 2 to 1—and by this it is meant that the secondary voltage is half the primary voltage—the current in the secondary with a load connected will be twice the current in the primary. Twice the current times half the voltage means equal power.

Now you can see how transformers save millions of

dollars. Suppose a power company supplies 110-volt D.C. to its customers, who use 10,000 amperes at an average distance of 10 miles from the generator. Suppose the power cable has two wires 3 inches in diameter, one the positive and the other the negative lead. The current passes through 20 miles of wire out and back. That much wire 3 inches in diameter has $\frac{1}{10}$ of an ohm resistance. Since a formula for power, as we found in Chapter 2, is $P = I^2R$, the power lost in the wires alone equals $10,000 \times 10,000 \times \frac{1}{10}$ or 10,000,000 watts, or 10,000 kilowatt-hours every hour. Since a kilowatt-hour sells for about 4 cents, the total loss due to resistance in the wires amounts to \$9,600 a day.

If the same company generated its power at 11,000 volts A.C. and put transformers near its customers which stepped the power line voltage down to 110, the turns ratio of the transformers would be 1 to 100. When the customers used 10,000 amperes, the current in the power line between the generator and the transformers would be only 100 amperes. The loss in the power line would be $100 \times 100 \times \frac{1}{10}$ or 1000 watts per hour. The loss is 24 kilowatt-hours at a cost of 96 cents each day. This difference pays for a lot of transformers. In fact it makes it economically *possible* to supply power to users who are at considerable distances from the power stations or in sparsely populated areas.

A.C. MOTORS

There are many kinds of A.C. motors. The motor in Fig. 5-15 will work on A.C. As the direction of the current changes during each cycle, the magnetic polarities of

both the rotor and the stator change at the same time and the driving force stays in the same direction. This design is useful when the motor is to be operated on either A.C. or D.C., but certain further refinements are required. Because of the changing field, a coil draws less current on A.C. than on D.C. You have seen the effect when you operated your relay as a buzzer. Simpler motors can be designed for use on A.C. by taking advantage of transformer action. Instead of using brushes and commutators or slip rings to get current into the rotor to make it a magnet, the current can be induced in the rotor by the stator. This kind of motor is called an *induction* motor. There are a variety of types. Since the commutator and brushes require repair more often than any other part of a motor, induction motors require little service. Induction motors must have some special provision for starting them because no force is exerted on the rotor when it is standing still. Self-starting induction motors are called *capacitor-induction* motors (or *condenser-induction* motors), *split-field* induction motors, or *shaded-pole* induction motors, and there are other types named in accordance with the kind of circuitry used to start them.

Another kind of A.C. motor is called the *synchronous* motor. Its rotor is supplied with direct current through slip rings. Its speed is constant, governed by the frequency of the A.C. and it is used where speed must not change. A modified form of the synchronous motor called the *salient-pole* induction motor is used in electric clocks. If the line frequency does not change—that is, if the generator speed is held constant—the clock will always tell the right

time. If the engine driving the generator slows down slightly, the power company will speed it up to give a little higher frequency than 60 cycles until the clocks catch up.

There are as many kinds of electric motors as there are uses for them. And there are many other uses for all the components you have learned about in this book. Look around your house. There are transformers to step down 110 volts for your door bell so that lightly insulated wire can be safely used, and there is a buzzer or bell that operates exactly like the one you made. The television set and the radio-phonograph use transformers to give voltages higher and lower than 110 volts, and they use capacitors and resistors and coils. Motors are everywhere—in the phonograph, the sewing machine, the refrigerator, the electric fan, the elevator, the electric clock, the mixer, the blender, the air conditioner, and the movie projector. The toaster employs resistance and so do the heater, the electric blanket, the automatic coffee maker, and all the light bulbs. There are coils in the fluorescent light fixture, and a buzzer in the electric alarm clock, and batteries in the flashlight and the portable radio. And there are many other electrical components which we have not mentioned in this book. We hope you will want to go on and learn the details of them for yourself.

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ABOUT THE AUTHOR

John M. Kennedy was born within sight of the Bronx Zoo, and perhaps this accounts for his interest in science—at least in part. He tells us that at fourteen he made and launched his own rocket. It soared out of sight but failed to go into orbit.

During World War II John Kennedy was a paratrooper, training troops in communications and commanding an air base north of the Arctic Circle in Greenland. After the war he spent two years in China with an oil company.

Mr. Kennedy is an electronics engineer, and he and his wife and daughter live in New York City.

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